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Analysis of LH_2 propellant system for civil hypersonic aircraft

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The challenge involving teams consisting of PhD, graduate and undergratuated students under the coordination of researchers and professors of different nationalities and different backgrounds. Teams will be led by members of the STRATOFLY consortium (POLITO, FICG and VKI). Each member can contribute through the design of a hypersonic vehicle concept, or through an in depth investigation of one of its most critical subsystems.
In order to allow the understanding of the following thanks to all my dear ones, I will continue this part in Italian.

Desidero ringraziare inanzitutto la Professoressa Nicole Viola per avermi dato l'opportunità di concludere il mio percorso di studi contribuendo alla trattazione di un argomento innovativo e stimolante, inerente al tema dei velivoli ipersonici.
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ABSTRACT

This thesis aims at highlighting the benefits and drawbacks of the adoption of liquid hydrogen in hypersonic vehicle concepts.
A brief overview of the technological challenges and solutions, environmental and economic aspects, is performed, including considerations on the aircraft and airport design, safety and handling. The analysis identifies and discusses multidisciplinary issues related to the development of a liquid hydrogen system that allows adequate levels of integration on the aircraft and a full infrastructure to support it. It also includes the means for delivery and storage as well as requirements, regulations and standards. Key factors that play an important role in pointing out the potential of liquid hydrogen and its impact on aviation are emphasized.
A simplified tank design approach is subsequently introduced, making benefits of models already available in literature about cryogenic tanks sizing. Even if a simplified approach has been followed, the tank model allows a first estimation of geometrical, mechanical, and thermal characteristics. A useful algorithm has been applied to a hypersonic aircraft configuration to properly evaluate internal and external volumes and relative weights.
In parallel, an ad-hoc created model has been developed in Matlab-Simulink environment, to simulate the entire propellant subsystem of the hypersonic vehicle. Thanks to the Simulink model, an in-depth investigation of the subsystem architecture is carried out, with the possibility of evaluating the impact of different feeding strategies. Moreover, a preliminary evaluation of the fuel mass exploited all along the mission and a prediction of the Center of Gravity (CoG) maximum displacement has been obtained and discussed. Eventually, the overall design process has been applied to the LAPCAT MR2.4 vehicle configuration, i.e. the baseline configuration considered for the H2020 STRATOFLY Project.

ABSTRACT (ITALIAN VERSION)

Questa tesi si propone di evidenziare i vantaggi e gli svantaggi dell'adozione dell'idrogeno liquido nei concetti di veicoli ipersonici.
Viene eseguita una breve panoramica delle sfide e delle soluzioni tecnologiche, degli aspetti ambientali ed economici, includendo considerazioni sulla progettazione degli aeromobili e degli aeroporti, sulla sicurezza e sulla gestione. L'analisi identifica e discute questioni multidisciplinari legate allo sviluppo di un sistema di idrogeno liquido che consente adeguati livelli di integrazione sull'aeromobile e un'infrastruttura completa per supportarlo. Comprende anche i mezzi per la consegna e lo stoccaggio, nonché i requisiti, i regolamenti e gli standard. Vengono sottolineati i fattori chiave che svolgono un ruolo importante nell'evidenziare il potenziale dell'idrogeno liquido e il suo impatto sull'aviazione.
Successivamente viene introdotto un approccio semplificato alla progettazione dei serbatoi, considerando modelli già disponibili in letteratura sul dimensionamento dei serbatoi criogenici. Anche se è stato seguito un approccio semplificato, il modello del serbatoio consente una prima stima delle caratteristiche geometriche meccaniche, geometriche e termiche. Un utile algoritmo è stato applicato ad una configurazione di velivolo ipersonico per valutare volumi interni ed esterni e i relativi pesi.
In parallelo, un modello creato ad hoc è stato creato in ambiente Matlab-Simulink, per simulare l'intero sottosistema propellente del velivolo ipersonico. Grazie al modello Simulink viene effettuata un'indagine approfondita dell'architettura del sottosistema, con la possibilità di valutare l'impatto di diverse strategie di alimentazione. Inoltre, è stata ottenuta e discussa una valutazione preliminare della massima di combustibile sfruttata lungo tutta la missione e una previsione dello spostamento massimo del centro di gravità (CoG). Infine, il processo di progettazione è stato applicato alla configurazione del velivolo LAPCAT MR2.4, ovvero la configurazione di base considerata per il progetto STRATOFLY H2020.

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1 INTRODUCTION

1.1 Overview of the recent Hypersonic Technology Developments

The aerospace industry, according to the experts in this field, clearly shows strong indications that air traffic will increase in the next decade and beyond. Europe continuously supports the development of futuristic technologies that could improve air transport, including the design of high-speed aircraft. Over the years, hypersonic flights have particularly been the focus of examination by aerospace research. New aircraft configurations, improvements in high speed propulsion engines and in aerothermodynamics, the need of high temperature resistance and light weight advanced structures are just some of the aspects explored in ATLLAS and LAPCAT projects funded by the EU. [1] The achievements of these programmes have resulted thanks to the definition of high level requirements, driven by new conceptual design, enabling the construction and manufacture of these vehicles and their systems. [1]
"Research project aims to identify new trajectories in unexploited space, to decrease noise and emissions, evaluating the climate impact and guaranteeing at the same time required safety standards for passenger transport, to evaluate the economic feasibility of the future operability of hypersonic vehicles." [2]
Since the dawn of aviation, mankind has been stimulated and motivated to cross long distances non-stop, in a very limited time. One of the baseline mission goals is indeed to drastically decrease the hours of long-range civil flight; to cover the route between intercontinental cities in about 4 hours or less instead of the normal 16 or more, thus making these distance flights more attractive. This would require a new flight regime with Mach numbers ranging from 4 to 8. [3], [1] At this high speed, travel time and range are just some of the figures of merit to consider for a high speed aircraft concept design. The distance depends heavily on the total available fuel mass, its energy content and consumption, during the entire mission. [1]

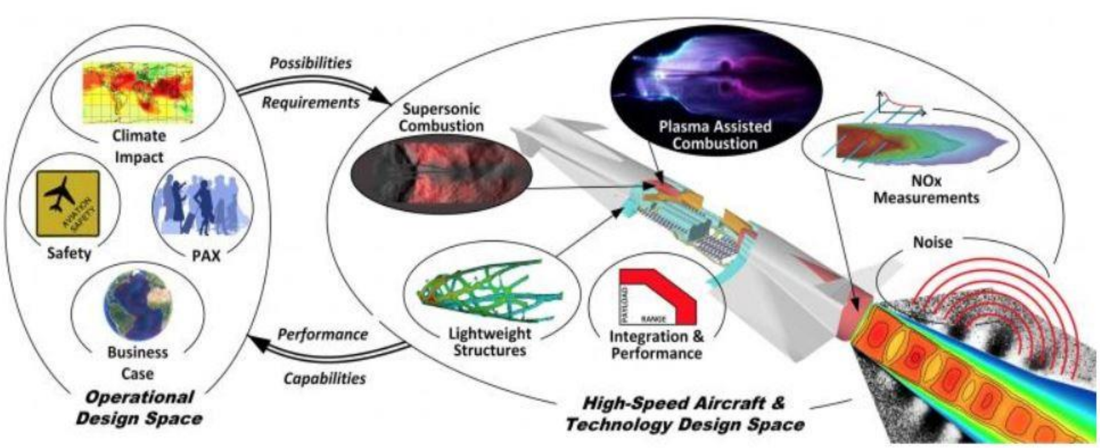

***Figure 1.1 Links between different and multidisciplinary domains* [2]**

In the 1930's the German, Eugen Sanger, designed the first hypersonic aircraft, the" antipodal Bomber". Although it has never been realized, it was expected to reach speeds and altitudes near the orbital ones, from which to begin a long descent, with successive "bounces" back to the dense layers of the atmosphere, in order to obtain considerable autonomy. [4] The Soviets responded to this study with the "Soviet antipodal Bomber", which was to address the achievement of antipodal distance by stratospheric cruising at hypersonic speeds, rather than with a suborbital trajectory. However, even this project has not been further developed due to technical problems and financial reasons. [4]

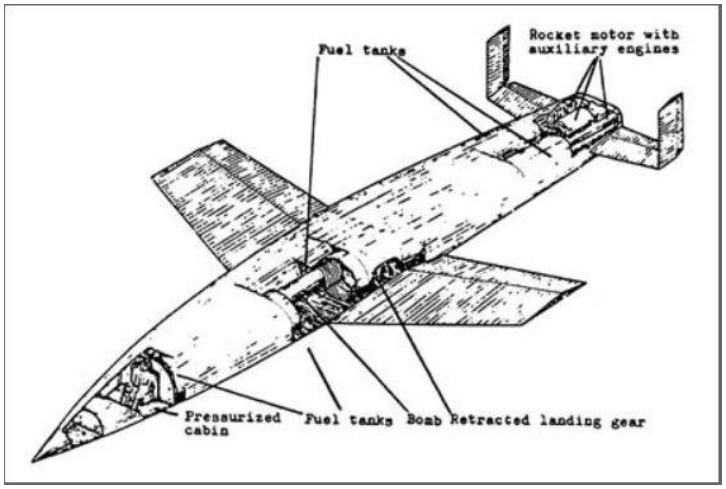

Figure 1.2 Sanger Antipodal Bomber

Only in recent years have NASA, ESA, China and private companies been working on more concrete prototypes and projects. The project ZEHST-Zero Emissions HyperSonic Transport is a planned supersonic airliner that uses, in succession, three different types of engines: turbo fans powered by biofuels for subsonic flight phases at altitudes further down 10 *km*, rockets powered by LOX and LH2 during the acceleration phase and Ramjets (powered by LH2) for hypersonic cruise. [4] It can be considered as a descendant of the Concorde airliner capable of flying at more than Mach 4 and can transport from 50 to 100 people 32 *km* above the ground. ZEHST would be able to fly from Paris to Tokyo in 2.5 hours, or from New York to London in an hour. [5]

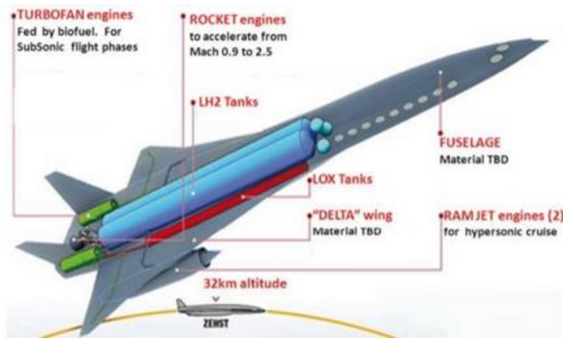

Figure 1.3 Zero Emissions HyperSonic Transport

SKYLON is an unmanned spaceplane designed by British company Reaction Engines Limited. This shuttle is intended to reach the Earth's orbit with a single stage, taking off and landing like a conventional aircraft. It is powered by two SABRE engines and presents different architecture, aimed at eliminating large displacements of the CoG with the progressive consumption of propellants. [4], [6]

Figure 1.4 Skylon on orbit

A team of Chinese experts has successfully tested an airplane capable of reaching 8,600 km/h of speed. I-plane could connect China and the United States in less than two hours. It could also become a deadly weapon or just stay as a project. The plane, seen in section, looks like a little "I", hence the name. The news regards the design: the aircraft relies on two wings, the upper one on the delta and the lower one on the reverse arrow. Moreover, the I-Plane wings are positioned so that the shock waves caused by the sound barrier (which can cause turbulence and resistance) are diverted in order to improve flight performance and stability. [7]
The LAPCAT-MR2, a Mach 8 hypersonic cruise passenger vehicle, is one of the different concepts studied within the LAPCAT II project commissioned by the European Space

Agency. It was designed to take off from Brussels airport, then fly to the North Atlantic and reach Australia after flying over the North Pole, in 4 hours. [3] It is an evolution of a previous vehicle, LAPCAT-MR1. The guideline was the optimal integration of a high-performance propulsion unit within an aerodynamically efficient wave rider design, guaranteeing enough volume for tanks, payload and other subsystems. [8]

1.2 Objectives and aim of the thesis

This work focuses on the analysis of the LH_2 propellant system for civil hypersonic aircraft. Nowadays, the development of the aeronautical sector could be limited by its impact on the environment. These considerations have led to the need for a clean, sustainable energy system and to require technological solutions to reduce emissions. It is therefore necessary to find an alternative that caters to the needs of society and does not place further burdens on the atmosphere. Liquid hydrogen appears to be one of the best available options for aviation and in a good position to replace jet fuel. In light of the results and challenges revealed by previous studies concerning liquid hydrogen in civil and space transport, the aim of this thesis is the identification of the key factors that play an important role in pointing out the potential of the liquid hydrogen. These key factors may belong to both the technological and operational domains.
The hereafter reported analysis will identify and discuss multidisciplinary issues related to the development of a liquid hydrogen system that allows a high level of integration on the aircraft and a full infrastructure to support it. This analysis cannot neglect issues related to delivery and storage as well as requirements and regulation.

From the technological perspective, an algorithm is presented to support the design of cryogenic tanks for hypersonic configurations, with appropriate shape, material and mechanical characteristics. This allows the customization of tanks on the basis of the amount of fuel requested for the mission.

In the second section of this document, a Physical Model generated using the Simscape Library of Matlab- Simulink is presented, as useful support for the evaluation of the entire propellant subsystem, including its main connections with the other subsystem (e.g. propulsion subsystem, etc..) and the feeding strategy. Moreover, the physical model can provide a useful support to the verification of tank volumes as well as for the estimation of fuel mass consumed during the mission.

1.3 Structure of the thesis

In Chapter 2, referring to the literature, the main properties of liquid hydrogen are presented, and its effects on the aircraft design and performance are analyzed. Particular attention shall be given to the hydrogen production, liquefaction and transport system. Standards, codes and requirements governing its storage, use and distribution into the chemical industry, in industrial processes and in space programs are well established, but this is a different situation and it is necessary to follow guidelines in terms of safety, human factor and no marginal performance. Starting from an overview of the current scenarios, the impact of all these aspects on cost estimation is investigated together with the identification of social and environmental issues.

Chapter 3 describes the case study considered and clarifies some of the assumptions made in the following chapters.

Chapter 4 looks in detail at the design of cryogenic tanks. The method investigates the implications of the aircraft type on the design of tanks.

In Chapter 5 the case study of the propellant subsystem of the reference aircraft is explored. After introducing the main functions of a fuel system and focusing on the definition with the architecture having been taken into account, the model created in the Matlab-Simulink environment is presented. It allows, starting from certain choices and data, the evaluation of propellant mass margins.

In Chapter 5 the results of the case study that was executed on the hypersonic aircraft are considered and discussed.

Conclusions are drawn from considerations and from the overall outcome.

2 HYDROGEN AS AVIATION FUEL

“Hydrogen is a versatile energy carrier which can be produced in various way from many sources. Its unique attributes such as global availability, safety, low mass and causing minimum pollution makes it an ideal fuel.” [9]

Numerous research have led engineers and scientists to attest the viability of liquid hydrogen as aviation fuel. Following the energy crisis of 1973, NASA and many other organizations have assessed alternative fuels to hydrogen, such as synthetic kerosene, liquid methane or biofuels. [9] The feasibility each fuel was evalueted from the point of view of cost, capital condition, and energy resource utilization, fuel production, airport storage, distribution facilities and use in aircraft and in particular, environmental compatibility. [10] In addition to the depletion of fossil fuel, there is increased awareness of the stress on the environmental especially due to pollution, acid rains and the greenhouse effect. These factors make hydrogen the most publicized environmentally benign alternative to petroleum.

The development of aircraft or rockets that use liquid hydrogen at cryogenic temperatures is a challenge. This requires new designs, new materials for tanks and insulation, safe placement, new pipes and pumps, safety systems, etc. [9]

2.1 Properties of LH_2

Hydrogen is the most abundant element in the universe and the first element of the periodic table. Since hydrogen readily forms covalent compounds with most nonmetallic elements, most of the hydrogen on Earth exists in molecular forms such as water or organic compounds. Thus it must be produced for its various uses. [11] In aviation and aerospace, hydrogen’s very low heating value (on mass basis) makes it competitive especially due to the essential weight limitations. It has low density in both liquid and gaseous state (14 times less than air). Although hydrogen can be stored in several ways, even when compressed at 164 bar and 288.15 K. Gaseous hydrogen offers a specific volume of 5.6-times the volume of LH_2, which means liquid hydrogen is the only viable form for long range aircraft. [12] Additionally, to allow the tank-wall thicknesses rise tremendously for the required internal pressures, greater than the pressures of the cryogenic storage solution for liquid hydrogen. Cryogenic liquid hydrogen can only exist at very low temperature, because the boiling point at atmospheric pressure is $-252.7°C$. Moreover, if stored at 1 bar it requires four-times the volume of jet fuel for the same energy amount. The critical point of hydrogen is at a temperature of 32.94 K and a pressure of 12.84 bar at which the liquid density is reduced to 31.40 kg/m^3. A careful insulation system is hence a fundamental consideration during the design process. [12], [13] The wide flammability range is an important chemical property of hydrogen, compared to hydrocarbon fuels.

Properties	Hydrogen	Synjet	Methane
Average Formula	H_2	$CH_{12.5}H_{24.4}$	CH_4
Boiling Point [°C]	-252.7	167.0-266.0	-161.3
Melting Point [°C]	-259.2	-50.0	-182.0
Density at boiling point $[\boldsymbol{kg/m^3}]$	71.0	800.0	423.0
Lower Heating Value $[\boldsymbol{kJ/kg}]$	119970	42906	48139
Flame Temperature [°C]	2158	2022	1973
Heat of combustion $[\boldsymbol{kJ/g}]$	120	42.8	50

Table 1 Properties of Aviation Fuels

It allows a very stable combustion over an equally wide range of operating conditions, enabling lower production of NO_x. Indeed, even though CO, CO_2, unburned hydrocarbons, and particulates are absent, oxides of nitrogen are still formed. It also necessary to consider its high flame velocity and low ignition energy. These positive combustion characteristics make hydrogen the main fuel for gas turbine engines, because the amount of NO_x, changes exponentially with flame temperature and linearly with reaction-zone dwell time. For this reason it will necessitates to work on these variables with the purpose to produce low quantities of NO_x, at least as low as those produced with the best carbon content jet fuel. [12], [9], [14] Figure 2.1 compares CO_2 emissions using the fuels kerosene, methane and hydrogen, all fixed to a constant heat release. [15]

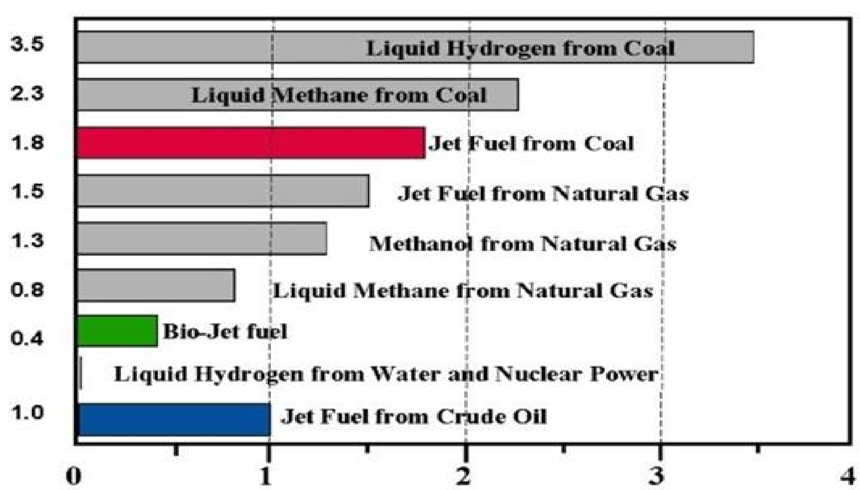

Figure 2.1 Relative CO2 emissions as compared to jet fuels

Another feature is the low toxicity and high volatility, that are quite important in case of spillage or leakage. The emission of liquid hydrogen, or of hydrogen just evaporated, in the atmosphere can create dangers of fire, explosion and embrittlement at low temperatures.
In spite of its simple structure, molecular hydrogen can exist in two distinct forms which differ in nuclear spin: orto-H_2 with nuclear spins of the two protons aligned in the same direction and para-H_2 with opposite spins of protons. At temperatures higher than, the equilibrium composition of the two form is called normal hydrogen. At the normal boiling point the equilibrium composition changes and shows a strong dependency on temperature (and indipendency on pressure). [12] If normal hydrogen is liquefied, ortho-H_2 converts spontaneously into para-H_2 under exothermic conditions. This leads to substantial boil-off rates depending on temperature. It's recommended to trigger this conversion during the liquefaction process to avoid the hydrogen conversion afterwards. Evaporation of liquid hydro- gen inside of a cryogenic tank can create a pressure increase. During the flight or ground phases, the pressure rises according to the boil-off rate inside the tank. Once the pressure reaches the maximum allowable tank pressure, a venting system might be realized to keep or decrease the pressure level. [13]

2.2 Effects on aircraft design and performance

The adoption of hydrogen as an aircraft fuel has impact on the design and performance of the aircraft itself and of its engines. Some characteristics are beneficial, some not enteraly.
As mentioned previously, the main properties of hydrogen are its very high heat of combustion and its very high specific energy content. A hydrogen fueled aircraft will require less fuel to complete the mission, compared to kerosene fueled vehicle. In LAPCAT-I, it was clearly demonstrated that liquid hydrogen is the only fuel able to achieve antipodal flight due to its high specific energy content. The design of hypersonic vehicle requires the development of efficient propulsion systems. This kind of aircraft is powered by scramjet engines: they are the only motors able to guarantee an hypersonic flight into a regime with $M > 5$. In fact, with a turbofan or turbojet, which use proper blades to compress air, above Mach 3 the hot air will melt them. On the other hand, ramjet use shock waves to reach higher Mach, but for Mach above 5, too much shock waves make the air flow subsonic in the chamber of combustion. The particular shape of the inlet of the scramjet solves these problems so the flow into the chamber of combustion keeps supersonic. Indeed, a supersonic combustion takes place.

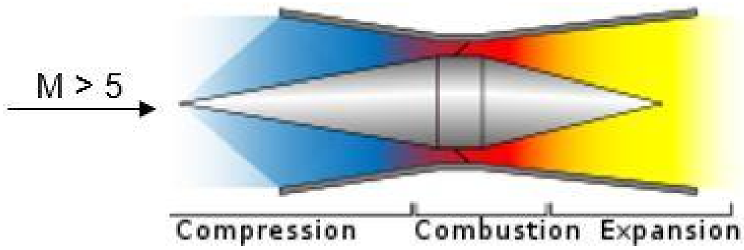

Figure 2.2 Scramjet Section

One of the most important benefit of this engine is that it doesn't need to carrier oxygen such as rockets, because it is a an air breathing. Scramjet compared with turbofan have a lower specific impulse I_{sp}, i.e. a measure of the propulsion system efficiency related to the exit velocity of the gases:

$$I_{sp} = \frac{T}{\dot{m}\, g_o}$$

Where T is the thrust, $\dot{m}$ is the mass flow rate and g_o is the gravitational constant. This value became lower when the Mach number increases, as it can be seen in the graph below.

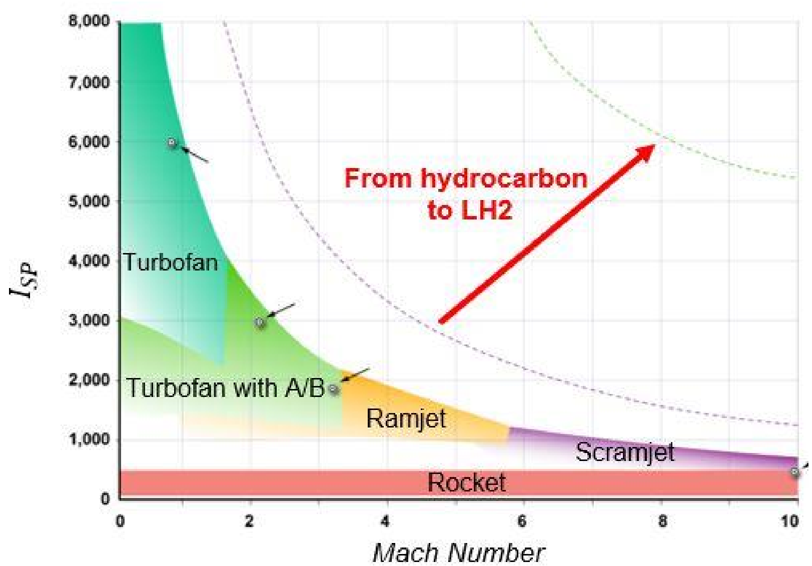

Figure 2.3 Specific Impulse vs Mach Number

The red arrow in the Figure 2.3 shows that is possibile to push forward the theoretical limit (even about double) of this term using LH_2 instead of Hydrocarbon fuels.
Obsvioulу, if the I_{sp} decreases, the thrust also does it, but the $\dot{m}$ increases, as previous mentioned. At this point, another important parameter can be considered:

$$SFC = \frac{\dot{m}\, g_o}{T}$$

The Specific Fuel Consumption increases when both $\dot{m}$ and the Mach number increase as can be seen in the graph:

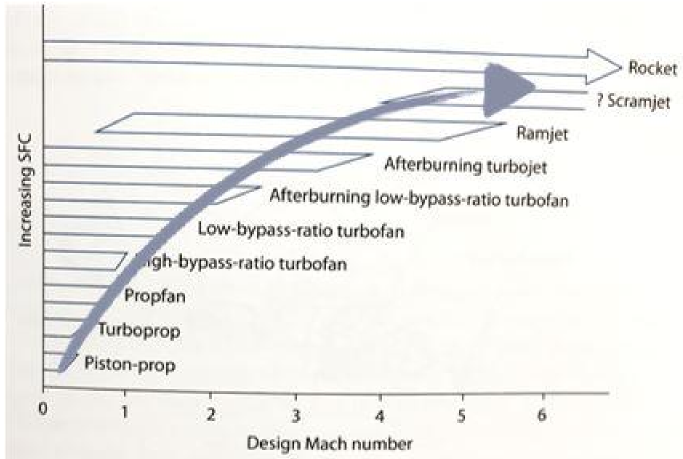

Figure 2.4 SFC vs Mach Number

This result shows the need to create bigger tanks in order to satisfy the request of higher fuel mass flow and the need to create engines with a larger inlet area in order to guarantee higher air mass flow. As always in the aerospace industry, these changes will affect the total design of the aircraft. So, an approach based on the integration will be applied.

Hydrocarbons lead too fast to a large gross weight (GTOW) prohibiting a fuel-efficient acceleration to cruise speed. Hence, using liquid hydrogen, the reduced fuel load permits a lower gross weight, enabling the use of smaller and also quieter engines. [8] The high specific heat capacity and low storage temperature could increase engine efficiency. As a consequence of this higher specific heat, the turbine expansion can be modified, which results in an energy specific fuel consumption benefit. The energy specific fuel consumption or ESFC is defined as:

$$ESFC = \frac{\dot{m}_f LHV}{T_N}$$

where $\dot{m}_f$ is the fuel flow rate, LHV the lower heating value and T_N the net thrust produced by the engine. It is a measure of how efficient the energy present in the fuel is converted into thrust. It is a direct consequence of the changed composition of the combustion gases and the amount of water vapor increased in the combustion chamber. [12], [9] The use of LH_2 in aircraft engines, necessisates modifications to the combustor and fuel system components, such as pumps, supply pipes, and control valves. In addition, a heat exchanger will be required for vaporizing and heating the cryogenically stored LH_2 fuel. [15] Exploiting the heat sink offered by the cryogenic LH_2 and the benefit of its cooling capacity, the engine performance could also significantly improve. Its high heat sink would reduce the demands on the heat exchanger effectiveness and thus its size and mass therefore. [12]

For super and hypersonic aircraft the cold hydrogen can be used to cool the structure and the skin of the aircraft that are vulnerable to aerodynamic heating. Hypersonic vehicles require the use of high temperature materials to withstand the high thermal fluxes during the trajectory. Moreover, the long duration of the mission requires the design of a thermal protection system able to withstand with the accumulated heat load during flight. [16] The extension of interfacing surfaces between different subsystem comprising tankage, cabin, propulsion plant and aeroshell was considered for the Lapcat-MR2 vehicle. The boil off within the cryogenic tanks is generated by the heat load which penetrates the aeroshell. A fraction of this gaseous hydrogen cools the passengers cabin. In line with this, the fuel boil-off is not considered lost as it is also used as coolant within the air-pack and the propulsion plant. It could be further used to cool down other components prior to injection into the combustion chamber. [16], [12]

Hydrogen has a low density and require more volume than kerosene fuel. It is necessary to find an aircraft configuration to accommodate the fuel volume. Because H_2 must be used in its liquid cryogenic form, aircraft design trade-off are essentials. To limit boil off, the tanks must have a low surface to volume ratio and an insulation system. In a conventional aircraft, insulation requirements mean that cryogenic fuels cannot be stored in the wings as hydrocarbon fuels can. The fuel is thus preferably stored in the fuselage. As consequence, the fuselages are generally larger with a higher wetted area and the wing size reduced due to the lower weight. At the same time, the low wing loading and lower lift-to-drag ratio comes from the low density and the low fuel weight. [15], [12] The finding of the most recent studies on the major effects of LH_2 on aircraft design and performance are summarised in the Table 2.

Properties	Effects
High heat of combustion	Reduced fuel weight
	Reduced gross weight
	Smaller and quieter engines
High specific heat	Reduced SFC
Low density	More volume
	Low wing loading
	Lower efficiency (L/D)

Cryogenic	Insulation system
	Heavy tank and fuel system
	Costant pressure to minimize boil off

Table 2 Effects of LH₂ on aircraft design and performance

2.3 Hydrogen Production, Liquefaction and Storage

Although hydrogen is the most abundant element in the universe, on Earth it cannot be found in its free o molecular state, but only in combination with other elements. In the combined form, it exists in substances such as petroleum, methane, coal, organic compounds and water. For this reason, it is necessary to produce it. In the current practice, 97% of hydrogen in the world is firstly obtained by decomposition of natural gas and methane and 3% by electrolysis of water. [17]
The most common method of producing hydrogen in large scale is the steam reforming of methane. The process consists in reacting methane CH_4 and water H_2O at temperatures around 700-1100 °C to produce syngas, a mixture of carbon monoxide and hydrogen:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

The heat required to activate the reaction is provided by burning part of the methane. Although the reaction is favoured by low pressure, because the H_2 obtained from it has high marketability, it is performed at high pressure. Further, at temperatures of about 130 °C the water-gas shift reaction can be used to recover hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Essentially, the oxygen atom is ripped from water to oxidise carbon, releasing the hydrogen that was previously bound to oxygen. In the final step, the hydrogen is separated from the other gas. This process has been so well established over the years that it is, therefore, the most economical. However, from an environmental point of view, the production of hydrogen from fossil fuels (even though more economical saving) contributes significantly to the release of greenhouse gases and other pollutants to the atmosphere. From this perspective, water is attractive raw material for the production of hydrogen. Being free from carbon, nitrogenous or sulfurous species, water would seem ideal for hydrogen production in large scale, contributing to the reduction of polluting emissions of the previously mentioned fossil-based processes.

Water electrolysis is a electrolytic process in which the passage of electric current causes decomposition of water to gaseous oxygen and hydrogen. The electrolytic cell is generally composed of two electrodes of an inert metal (e.g. platinum), immersed in an electrolyte solution and connected to a current source. At the cathode the hydrogen ions acquire electrons in a reduction reaction that leads to the formation of gaseous hydrogen:

$$2\,H_2O \;+\; 2\,e^- \;\rightarrow\; H_2 \;+\; 2\,OH^-$$

At the anode:

$$2\,H_2O \;\rightarrow\; O_2 \;+\; 4H^+ \;+\; 4e^-$$

From the sum of the two previous half-reactions the following complete reaction is obtained:

$$2\,H_2O \;\rightarrow\; 2H_2 \;+\; O_2$$

Nevertheless, this reaction is not spontaneous at ambient pressure and temperature. Under this conditions it can only occur by supplying energy as electrical work in an electrochemical reactor. Today, the efficiency of electrolysis is around 70-80% and depends on the capacity of the plant and technology used. [12] Significant obstacles are due to the limited amount of LH_2 product and to high costs due to the use of electricity. The process is still therefore being severely tested by a sort of incompatibility between different factors: efficiency, stability and low costs.

In the last few years, researchers have succeeded in producing hydrogen from renewable sources, in particular by dark fermentation of biomass. Biomasses are a renewable and available source, but are renewed in a far shorter time than lower than those of fossil fuels. In general, the ”biomass” is defined as the biodegradable fraction of a wide variety of products and waste. Even the use of various kinds biomass for the biological production of hydrogen can have economic, political and environmental impacts. Economic costs that depend heavily on the cost of raw material must be taken into account. [18] To satisfy the annual fuel consumptions of aviation alone, requires use of a wide surface area, that is currently impossible to provide. Moreover, it must be said, that by using waste biomasses, the CO2 emission would be zero because the CO2 emitted during the production of energy from biomass is equal to that absorbed during the growth of the same. [12], [18]

In a nutshell, currently, producing hydrogen turns out to be a challenge that is principally based on the environmental impact and costs. The best option appears the electrolysis of water coupled with a renewable energy source such as photovoltaic cells and wind turbines. Even in this case, however, we will need to consider all the problems that arise. It will be necessary to build technological industrial facilities with new technologies that are environmentally compatible with LH_2 production, since world production currently does not cover the daily needs of even 20 airports.

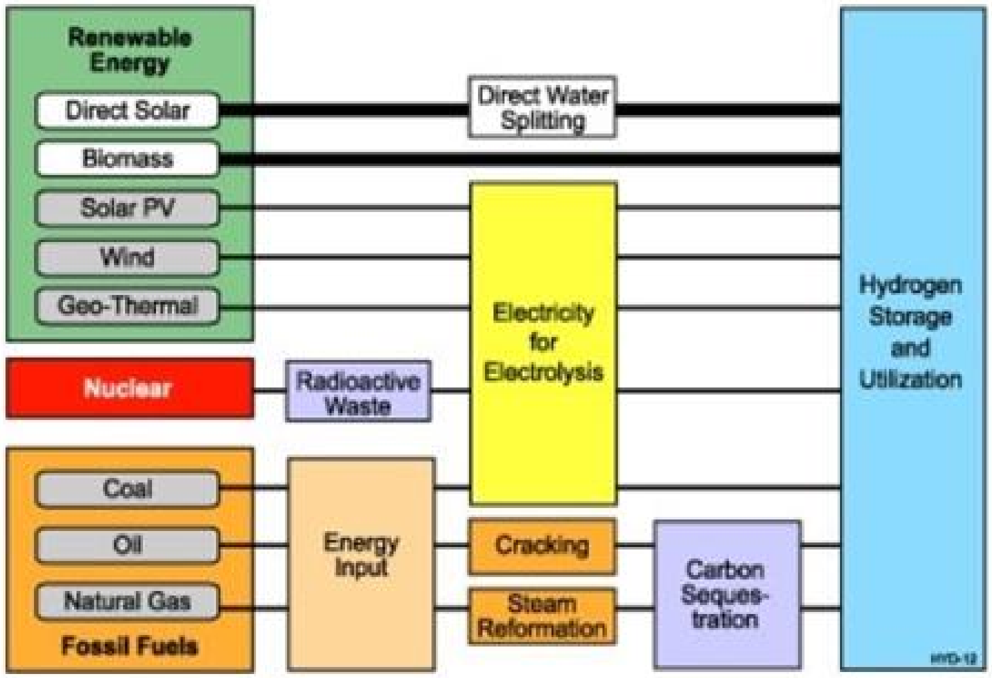

Figure 2.5 Hydrogen Production Paths

Liquid hydrogen requires a temperature of 20 *K* to be stored as fuel on board the aircraft. Before lowering its temperature, however, it needs an intermediate phase to allow for the elimination of impurities that generally solidify at higher temperature than the liquefaction of H_2. Currently the hydrogen liquefaction can be obtained by using the Claude cycle, by Brayton, or by exploiting the magnetothermical properties of some materials. One of the main fears related to liquefaction derives from the fact that under these conditions, the substance is at temperatures comparable to that of boiling and consequently any absorption of heat through the liquid leads to the evaporation of part of the substance. For this reason, a considerable amount of the required energy is spent to bring the temperature down to below the critical point. Hydrogen liquefaction involves an energy expenditure of 30-40% of the intrinsic energy content of the liquid. Firstly, pure hydrogen gas must be compressed to a high pressure and thus its temperature also rises. The hot pressurized gas is then passed through two heat exchangers and again combined to be passed through a tank containing liquid nitrogen, finally passing through another heat exchanger. Experts have investigated the different steps of the liquefaction process in detail, using innovations and greater integration in an effort to reduce specific energy consumption by 50% compared to the state of the art, while simultaneously reducing investment cost. Hydrogen liquefaction costs decrease with production rate. Once liquefied, the hydrogen must be stored. Any passage of heat through the walls of the liquid container cause the evaporation of a part of the hydrogen with consequent loss of gas and this, ultimately, is reflected in a loss of efficiency of the system. The use of cryogenic containers with high thermal insulation can mitigate the problem, but never eliminate it. They must be designed in such a way so as to minimize heat propagation by conduction, convection and radiation and any thermal contact, or using materials with low thermal conductivity. Since heat losses are commensurate with the size of the total surface area, most of the liquid hydrogen tanks are spherical in shape. In fact, among the solid forms, the latter is characterized by the lowest surface area per unit of volume. On the other hand, it should be noted that cylindrical shapes are preferable for their ease of construction.

Figure 2.6 Example of LH2 containers

2.4 Distribution and airport service

Trasporting and storing hydrogen as cryogenic liquid presents risks. The physico-chemical characteristics such as the high flammability and/or explosiveness, require the adoption of particular and stringent safety measures during the transport, storage and use.
The decision on modes of hydrogen transport and distribution from the production plant is therefore essential.
Hydrogen production facilities would have to be constructed along with liquefaction and LH_2 storage facilities. An option could be the construction of large-scale centres with trailer trucks and a railway near the airport. An entire fuel distribution system would have to be created, which would increase in complexity with the distance. Several extensive hydrogen pipeline networks exist throughout the world, for example the Air Liquide Network in North Europe which covers a distance of 1500 *km* and connects various ports and chemical industries. [12]
Transport pipelines of gaseous hydrogen are only viable in case of large volumes and shorter distances, but will not be advantageous due to the high evaporation losses caused by heat entry. In this case, liquefaction facilities are required at the airfield. The airport must then have a large space dedicated to the production of liquid hydrogen. At the same time, real supply stations or systems suitable to supply liquid hydrogen aircraft will be required. It is envisaged

that the delivery of LH_2 to the aircraft would be done by tanker trucks and pipelines. This implies a need for high investments for infrastructure (such as filling, exchange system) and would be technologically more challenging. Actual refueling systems would have to be converted to deliver the cryogenic hydrogen. The selection of materials, means and devices must be managed with care. Experiences gained and technologies developed for refuelling cars with LH_2 tank can be useful for an aircraft LH_2 refuelling system. [19] Ground Servicing systems must be reviewed and verified capable of offload safety before propellant is loaded. The special equipment and personnel training for safety during and after servicing must be available and functional. The service equipment, procedures and personnel also must be checked out and certified ready for propellant service, especially for spills and leaks. Hence, a large amount of hydrogen must be present and stored at the airport to deal with aircraft demand. In all researches, liquid hydrogen is delivered in large vessels and delivered through underground insulated pipelines in positively ventilated tunnels or in open trenches. To minimize boil off the tanks could be submerged in water. A fuel tanker/hydrant service vehicle or a fixed hydrant around the gate could be used for fueling the plane. These options would require a small cost investment, but higher operating costs. [12]

The exploitation of liquid hydrogen by all the vehicles and machines at the airport, such as buses and baggage trucks, might also be considered. The design features of a liquid hydrogen delivery system is determined by the demand. To design and implement LH_2 facilities involves financial risks. The investment risk is mainly due to operating costs, in addition to the operation of the plants during the first phase of development. Synergies between LH_2 aircraft and other hydrogen applications inside or outside airports should therefore be considered. Hydrogen fuelled ground support equipment and vehicles, small applications and airport bound land-side traffic (e.g. buses, taxis, etc.) will increase the overall hydrogen demand at the airport, and hence cause economy of scale effects. [19]

The use of equipment in common or at the same time the exploitation of the boil off mass, which could be preferred by these applications, could therefore lead to a reduction in costs.

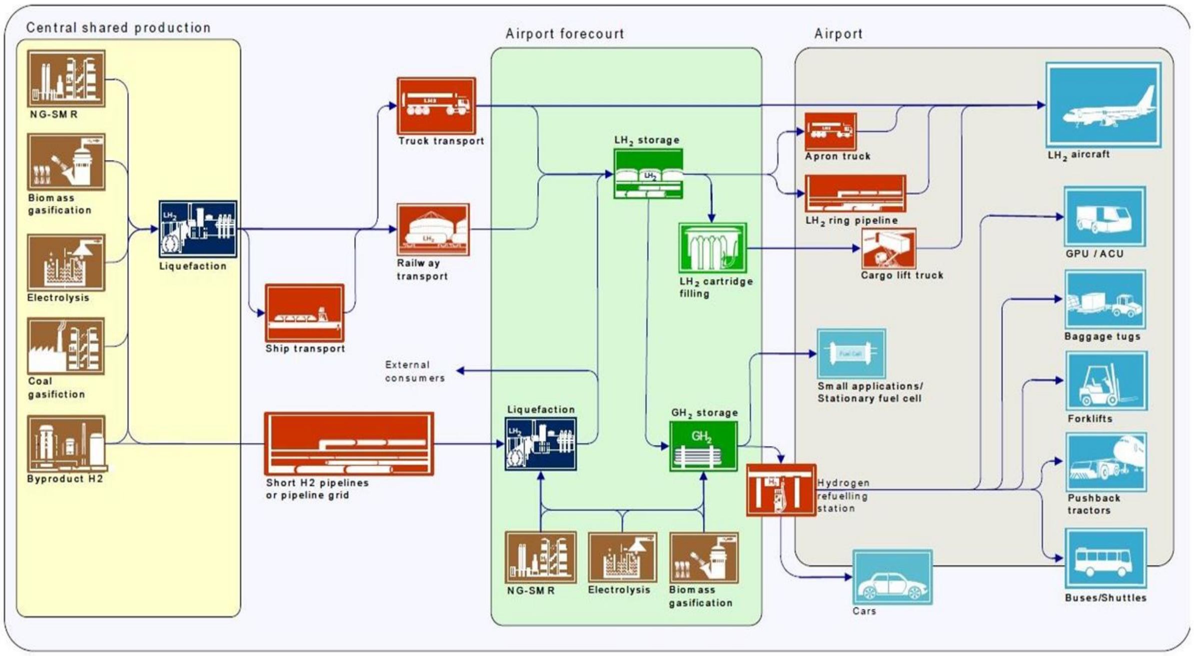

Figure 2.7 Exploitation of Liquid Hydrogen **[19]**

A first service station is operational in the Berlin airport area. Implementing and expanding a network such as this for the distribution and use of hydrogen is a fundamental requirement, especially in trying to make the most of its benefits, such as its environmental compatibility. In the future, use of hydrogen in the road transportation sector is expected to produce a significant increase in demand for it, especially with the introduction to the market of vehicles powered by fuel cells. This will lead to a greater availability of hydrogen and maybe reduce delivery distances. The successful introduction of hydrogen as a fuel will also depend on its acceptance in public opinion.

2.5 Impact on aircraft safety and handling

Liquid hydrogen use impacts both on aircraft safety and handling, on the airport itself an on the launch site of spacecraft.
Leakage of gaseous hydrogen's poses a major risk due to its high rate of diffusion in air along with its low density and low viscosity. The dispersion phenomenon can occur on any occasion, even in cryogenic storage. In reality, a spill of the substance in an unconfined open environment does not involve particular safety problems because the gas is immediately dispersed without the formation of clouds. The most dangerous is a leak in a confined space. It is therefore necessary to implement practices suited to the distinct characteristics of hydrogen, such as the tendency to escape through small openings, compared to conventional fuels. Using cryogenic tanks, as in the case of hypersonic aircraft, it is essential to minimize the refueling time and the boil off losses in order to maintain the temperature at cryogenic

values. Before carrying out maintenance or inspection, the tank's temperature must increase, it must be emptied and purged with inert gas, which is then replaced with air. Similarly the refueling must be preceded with an inert gas purge before filling with liquid hydrogen. These procedures ensure that hydrogen does not accumulate in certain areas. In the event of extensive hydrogen accumulation in an enclosed space, asphyxiation problems can occur. The advantage of to be a volatile fuel is that in the event of a crash if the spill ignites, the duration of LH_2 would be quite short hence the fuselage would not not be heated to the point of collapse. Passengers would have more chance of survival and of not being killed by flames and fire. [12], [9] The buoyancy of hydrogen can also be used to manage risks associated with fuel handling by using internal partitions and differential pressurisation. This can be done by locating the potential source of ignition below the level of the equipment from which hydrogen may leak and accumulate and ensuring adequate ventilation. [20] LH_2 tanks are more rigid than conventional ones and less inclined to rupture. Moreover, stored at lower pressure, the probability of fatigue induced structural failures is reduced. The containment of liquid propellants and supporting fluid systems must be designed and tested for minimizing hazards and cascading failures, as the reduction of the capacity of the propulsion system and accomplishing the mission in safety. Propellant system devices, such as filters, pumps, isolation valves and pyro valves used as isolation for safety and reliability during the ground operations, are indispensable and require accurate engineering due the cryogenic conditions to which they are subjected.[18]

A liquefaction facility incorporated into an airport requires careful considerations. Although liquid hydrogen is not corrosive or poisonous, contact with elements at cryogenic temperatures can cause problems and injuries. Airport personnel in contact with such systems require specialist training. As already mentioned, it is necessary to implement technologies, procedures and policies for a safe and economical LH_2 management. Current design amendments prescribe a limitation of incidents within certain boundaries by enforcing certain distances for safety or protection and implementing strict controls and restrictions in the access to LH_2 reserves. Airports will have to evolve in order to regularly host hydrogen aircraft and also guarantee operations, maintenance and support for all vehicles. [21]

2.6 Regulations, Standards and Requirements

Standards, codes and requirements govern storage, use and distribution of a large quantitaties of liquid hydrogen in chemical industries, industrial processes and as rocket fuel. This is a different situation and it is necessary to establish guidelines to assure the design of successful and safe hydrogen systems.

The National Aeronautics and Space Administration has estabilished a standard for hydrogen system design, material selections, operations, storage and trasportation. The guide contains information about properties and hazards, facility and components design, material compatibility and detection. It also covers various operational issues and emergency

procedures. All equipment for hydrogen systems must be compatible with the physical and chemical properties of LH_2. Also personnel involved in equipment design and operations planning must be trained and accept standards and the regulatory code to eliminate and minimize accidents. [22] For example, all hydrogen systems must have adequate ventilation to menage leakage and reduce potential ignition sources. These must be eliminated or isolated. To detect and control the possibile effects of tanks failing, spills, embrittlement and abnormal conditions, safety and warning system that include sensors and devices that emit audible signals, should be implemented and installed. The analysis of risks and dangers and the identification of the factors that can cause failures in systems, allows fot the design of suitable procedures and regulations. Vessels failure can be avoided by limitating the excessive pressure caused by heat and including a pressure relief system. The required capacity of pressure relief of any device should include consideration of all the vessels and piping system it protects. [22]
A hydrogen system will involve a multitude of materials with different characteristic. Compatibility with the operating environment, corrosion resistance, easy fabrication, assembly and inspection and thermal properties at cryogenic temperatures are just some of the aspects to consider for the selection of the material for hydrogen applications. Many hydrogen material problems involve the use of an unsuitable material. Good quality control procedures should be carried out. Materials should be tested and anlyzed under various conditions. The design of piping for hydrogen systems should consider the pressure, the temperature and the applied force. All piping should be periodically tested and recertified. The loading should include those introduced by vibrations, shock, thermal expansion and contractions. Each section of cryogenic piping should be equipped with protection devices to control the pressure. The various piping should be assembled with the specified requirements of the engineering design.
“The safe and successful use of hydrogen starts with the knowing of and adhering to appropriate standards and guidelines for the design of the facilities.” [22]
The procedures for LH_2 use in facilites should include a check list to perform each operation: off loading, loading, LH_2 transfer, transport, manufactor, inspections, certifications, emergency actions. All to protect personnel, facilities, infrastructures, systems and equipments.
As the goal is an economy based on hydrogen as an energy vector, in parallel to the development of systems powered by liquid hydrogen, it will be fundamental to adapt the current rules, standards, codes in force, for examples in space programs or in chemical industries, to this situations. The efforts and resources of government and private entities, organizations or the users must be devoted to identifying problems and issues related to the applications of liquid hydrogen and validating methodologies for safely handling of large amounts.

2.7 *Economic Assessments*

To understand the feasibility of high-speed aircraft, an economical assessment of the operating costs and price of the ticket must be made. Particular attention has to be given to the estimation of fuel costs for hypersonic transportation systems, which can reach up to 90% of the overall Direct Operating Costs. [23] The evaluation of the impact of liquid hydrogen on DOC for an hypersonic transport system, is carried out by a methodology that, starting from the current production scenarios, investigates technological improvements which allow the increment of the production rate.

In the history of aviation and space travels, hydrogen has always been a source of energy and power on board, as propellant or not, and allowed to meet all design requirements in terms of effectiveness, safety and performance. However, despite the exploitation of LH_2 propellant in space propulsion systems during the 20th century, very few models, that predict the influence of fuel costs during the design phases of hypersonic aircraft, have been implemented.
As previously mentioned, liquid hydrogen is one of the most suitable and attractive fuels for hypersonic applications due to its properties, such as the highest specific calorific energy or environmetal compatibility with low CO_2 emissions.
The carried out studies reveal that the cost of liquid hydrogen is mainly influenced by:

- Geographical areas where LH_2 is produced;
- Daily production rate;
- Production process. [23]

If we consider hydrogen production by electrolysis of water and its subsequent liquefaction, the cost is mostly influenced by the amount of electrical energy used during these processes. Liquid hydrogen produced in the EU is more expensive than that produced in the USA. This is mainly the result of higher cost of electricity, as well as the cost of investment in infrastructure and manufacturing plant. On the other hand, unit cost decreases as the amount of LH_2 produced per day increases.
NASA suggests a cost model to obtain the impact of fuel cost on DOC for hypersonic transportation system. The fuel cost is determined by multiplying the amount of fuel used per flight including reserve allowances by the fuel price per unit weight:

$$DOC_{fuel} = 1460 \frac{C_f \left(\frac{W_{ft}}{W_{GTO}}\right)(1 - K_R)}{LF(\frac{W_{PL}}{W_{GTO}})\ R_T} \quad [\frac{\$}{ton\ mile}]$$

Where:

- C_f is the cost of fuel per unit weight evalueted for different productive scenarios;
- W_{fT} is the total fuel mass per trip;

- K_R is the reserve fuel fraction

In particular, the fuel price is expressed as:

$$C_f = C_{f_{electrolysis}} + C_{f_{liquefaction}}$$

It is important to note that the final fuel cost is given by the sum of all the costs incurred during each phases of the production process.

The exact breakdown between electrolysis and liquefaction was unknown, but adopting the study suggested by ESA, liquefaction cost constitutes almost 22% of total LH_2 production cost process and decreases as the production rate increases. Research studies thus indicate an urgent need for technological improvements to LH_2 production scenarios so as to increase the quantity of fuel produced per day. [22]

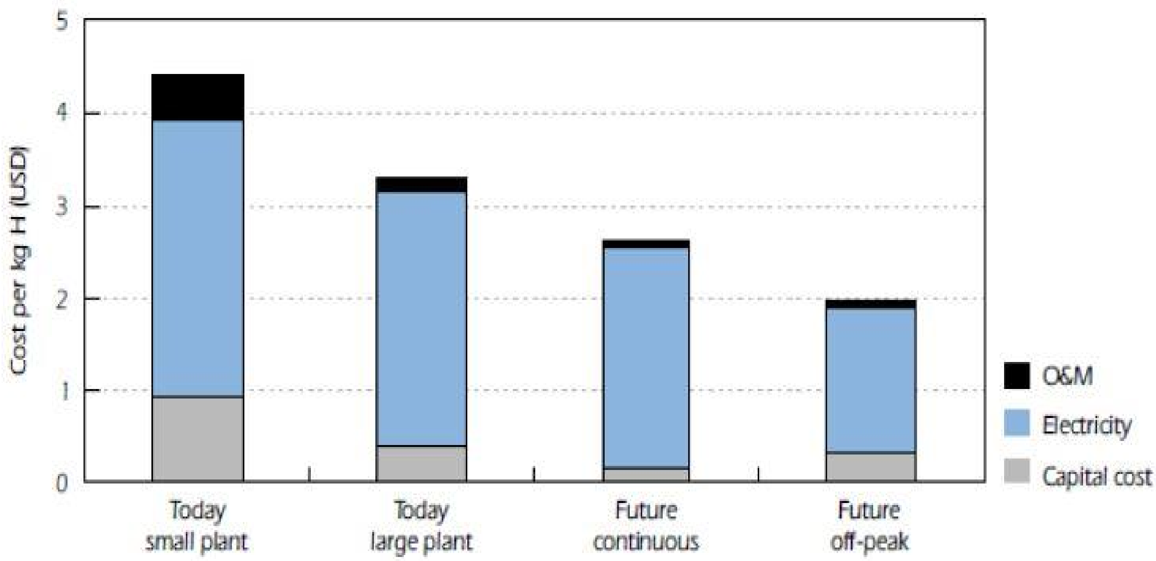

Figure 2.8 LH2 production cost (Electrolysis only) for different US scenarios **[23]**

The exploitation of hydrogen fuel for hypersonic applications is thus mainly hampered by the impact of cost and handling. The idea of hypersonic transport system development projects is to evaluate other large scale production methods besides water electrolysis, in order to understand how these can directly influence operating costs and , taking into consideration social and environmental issues, eventually choose the best option for the introduction of technological improvements.

3 CASE STUDY: STRATOFLY

STRATOFLY is defined as "Stratospheric Flying Opportunities For High-Speed Transportation". It is an international engineering project funded by the European Union's Horizon 2020 research and innovation programme. The project studies the feasibility of implementing civil stratospheric high-speed flights. The exploitation of stratosphere, which is the highest breathable layer of the atmosphere and extends up to 50 km, becomes necessary due the expected increase of the number of trasported passenger of airplane in the next decades. [24]

The objectives of the STRATOFLY project are the following:

- To drastically reduce transfer times for long-haul civil flights;
- To allow the sustainability of new air space's exploitation, decreasing noise and emissions and guaranteeing required safety levels for passenger transport;
- To estimate the economic sustainability of the future operation of high-speed vehicles;
- To achieve the goal of future reusable space transport systems;

STRATOFLY project has a high multidisciplinary structure and consists of two design spaces, technology and operational, that interact with each other.

In particular, the Stratofly research also aims to the refinement of the design and concept of operations of LAPCAT-II MR2.4, that has been selected as reference vehicle. [24]

Figure 3.1 Lapcat MR2.4

STRATOFLY hypersonic vehicle will fly at Mach 8 above 30 km of altitude and board at least 300 passengers, performing an antipodal transport mission. STRATOFLY vehicle technologies can thus represent crucial steps to achieve the goal of future reusable space transport systems. The concept provides for the optimization of system integration and performance, in particular between propulsion units and aerodynamic efficiency, thus guaranteeing the volume of the tanks and the storage of fuel, payload and all the necessary subsystems. The idea is to create an aircraft that can perform a hypersonic flight from Europe to Australia, flying over the North Pole, following the Bering Strait and avoiding inhabited lands. [24]

Figure 3.2 Example of Trajectory **[2]**

3.1 Propulsion and Propellant Subsystem

The optimization of the trajectory from Brussels to Sydney of LAPCAT MR2 has allowed the total travel time to be reduced to *2h55m* with an estimated consumption of 182 tons of fuel. The mission is divided into specific phases with different speeds, altitude and manoeuvres. The first phase is takeoff, followed by an acceleration phase. The second phase consists of a subsonic cruise at Mach 0.95 for about 240 kilometers to reach a speed and altitude suitable for a second acceleration, the second phase which increases the speed up to Mach 4, followed by the third acceleration phase to reach Mach 8. The hypersonic cruise is performed at an altitude of 32-35km. The final phase is an unpowered descent and a horizontal landing. [25]
The mission profile is is shown in Figure 3.2.

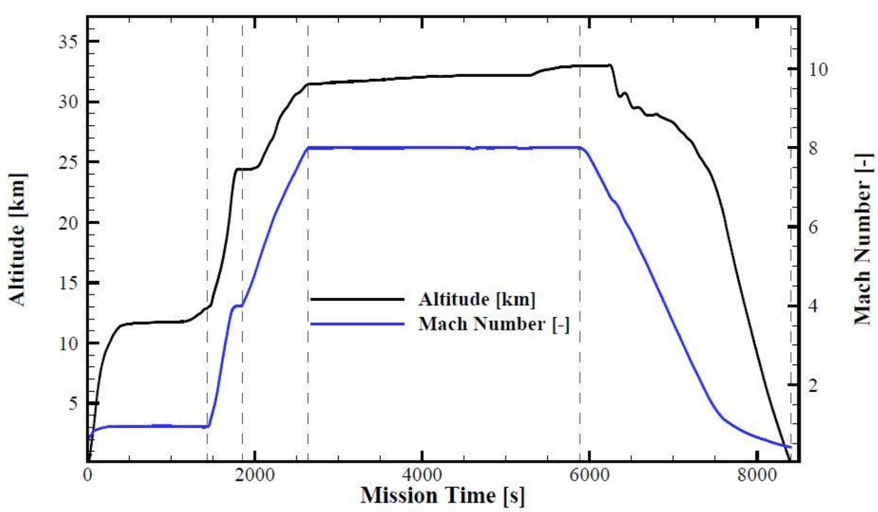

Figure 3.3 Mission Profile **[25]**

Two types of engines are used to execute the mission.
The first type of engine installed allows to perform subsonic and supersonic phases and is connected to the intake to provide the necessary flow: Air Turbo Rocket engine (ATR). A two-section nozzle is installed on the back of the unit. The first section acts as a combustion chamber to ensure supersonic expansion in the second section. Then after the expansion at the end of the intake, there is the combustion chamber that feeds the Dual Mode Ramjet. Since the mission involves a Mach 4 phase and then a Mach 8 phase, it is necessary to reach the appropriate speed to start the operation of the DMR engine, so the ATR is installed to allow the correct acceleration to be achieved before the hypersonic cruise.
Summarizing then, from takeoff to the Mach number of about 4, the ATR works. It consists of 6 engines divided into 2 spans (each with three engines) integrated. In order to reach the expected hypersonic speed, the vehicle works with the DMR system able to go up and down to the cruising phase. This engine is characterized by the already seen two-section nozzle. [8]

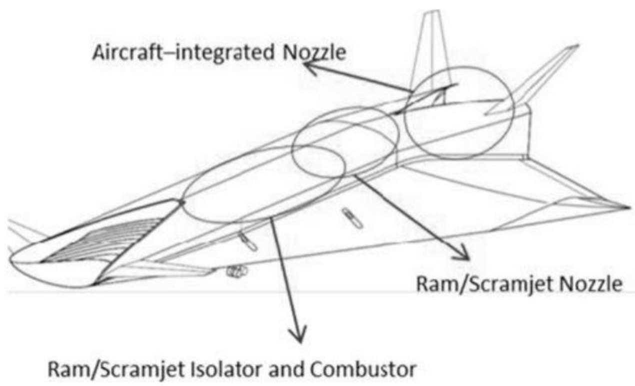

Figure 3.4 Propulsion Unit

Based on the mission profile, propulsion system and TEMS requirements, the amount of fuel required for the mission is distributed in the aircraft tanks located in the fuselage and wings, respecting the constraints, such as the location of the passenger compartment.
The reference configuration of LAPCAT MR2.4 has eight tanks: Body Center Aft Tank (BCAT), Body Center Forward Tank (BCFT), Body Side Aft Tank (BSAT), Body Side Forward Tank (BSFT), Wing Tank (WT). It should be noted that there are two units of each body side, forward side and wing tanks. This architecture is used as a starting point for the STRATOFLY aircraft configuration.
STRATOFLY research provide a revision of the propellant system of LAPCAT MR2.4 for several reasons:

- the external shape and the structure of the entire aircraft are currently under review;
- different propellant mass is estimated, having considered the reignition of ATR engines to perform the landing phase;
- the tank locations have to be revised based on their fuctions;

- as yet no propellant strategies have been defined;
- the CoG's movements during the mission phases have not yet been evaluated and consequently no weight and stability analysis has been carried out.

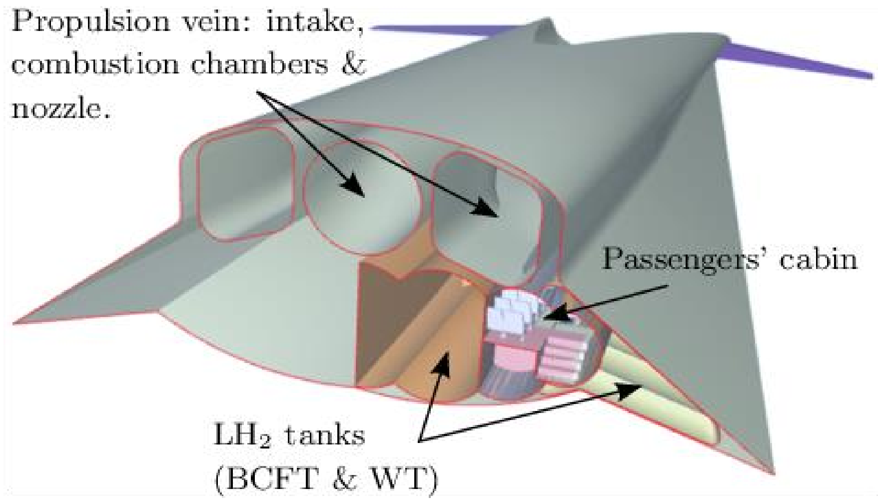

Figure 3.5 LAPCAT MR2 Rear Cut Section **[26]**

The estimated volume to accommodate the propellant subsystem is about 3000 m^3. The propellant system consists in fuel containment system including the fuel, the insulation system and the fuel delivery system (valves, pumps, pipes, etc.).
It is necessary to underline the need to estimate the construction characteristics of the tanks because they are elements that occupy a lot of volume. Unfortunately, the volume "stolen" from the insulation system is a very important slice that can not be overlooked.
One of the most significant integrated technologies on board the aircraft is the Thermal and Energy Management System (TEMS) responsible for providing the need for cooling for passengers and crew to ensure comfort but also to protect all systems (and subsystems) from high temperature fluxes, due to the propulsion system and external heat flows from the hypersonic velocity. Since during almost all the phases of the mission but in particular during the acceleration phase an excessive amount of heat passes through the airframe, the tanks are subject to the phenomenon of boil off. The idea of the STRATOFLY project then is to reuse the boiling fuel for cool the equipment before injecting it into the combustion chamber and balancing it. TEMS is therefore characterized by a high level of complexity and interfaces with different systems such as the propellant system. [16]
In this work, however, the integration of TEMS with the propellant system will not be taken into account, but the main objective is to identify the correct architecture and hierarchy of aircraft tanks that allows to meet the mission requirements and at the same time to size the insulation tanks system to minimize the boil off.

4 CRYOGENIC TANKS

The correct design of lightweight and highly insulated cryogenic tanks for liquid hydrogen storage is a key challenge to enable hydrogen-powered aircraft, especially if the operating conditions are those of hypersonic flight, where the high fluxes need to be struggled.
Since the 1950's, NASA and Lockeed Martin have investigated the implication of cryogenic hydrogen as fuel and accordingly focused their efforts into researches to reduce mass and weight of the current types of tanks used in conventional aircraft and space applications.
Engine design influences tank design and tank design influences the design of the entire aircraft. Aircraft and engine determine the fuel mass to be stored and tank dimensions, but the sizes affect aircraft weight. The link between these three elements is therefore intensified. [12]
Gaseous hydrogen has a lower density than liquid hydrogen and requires high pressure tanks, with greater structural strength. They are therefore heavier than cryogenic tanks at lower pressures, which instead maximise hydrogen density and enable significant decrease of mass and volume. Because of their excessive weight and volume, high-pressure gas storage appear to be unusable for hypersonic aircraft. Previous studies on cryogenic tanks discuss the storage dimensioning only on conventional aircraft geometries. Future aircraft concepts provide more volume especially in the outer and rear fuselage parts and the use of cylindrical and elliptical tank designs appears to be enabled. More complex tank geometries, such conformal tanks are also feasible. [13]
However, it is important to note that cryogenic storage imposes operational constraints on the fuel system:

- It requires an insulation layer to maintain cryogenic temperatures and prevent boil off.
- Tanks require a constant pressure, around $1.45x10^3 Pa,$ to minimize boil off. A venting system may need to be implemented.
- Specialized procedures and equipment for liquid hydrogen handling.
- Cryogenic tanks and piping must be sealed off from the armosphere, because if the air entered, due to low temperature, it would block the flow line.

As can be seen, the main components are the tanks and the insulation. [26]

Once the fluid to be stored is introduced, it is possible to discuss the criteria and constraints required for the cryogenic tank design approach. The following sections explain some key aspects on which the work presented in this thesis have focused.

4.1 Tank Configuration

4.1.1 Integral vs non-integral tank

The first choice to be made and which has a great effect on the aircraft structure and design is between using integral or non integral tanks.
The integral tanks are provided of the sealed compartments that the structure of the wing or the fuselage provides. They must be capable to withstand not only the fuel holding loads, but

also the stresses affecting the structure of the aircraft during the mission. Because there is no external surface that protects against possible damage, aerodynamic heat and other loads during flight, extra protective panels must be positioned on the external surface of the tank and over the insulation. These cannot be completely removed for inspection and they have special panels to allow internal inspection, repair, and overall maintenance of the tank. Most transport aircraft use this fuel storing system. It has a great structural resistance and allows to have a saving in terms of weight.
Non integral tanks only serve to contain the fuel and they must be attached to the frame and supported. Their task is simply to withstand fuel holding loads, thermal stresses and pressurisation.
Before choosing between these two configurations, the maintenance aspects must also be evaluated. Inspections to check for leaks or fractures must be carried out regularly, due to the use of cryogenic hydrogen. As already mentioned, maintenance operations on integral tanks are relatively easily facilitated by the removal of some panels, although it would be necessary to assess the space restrictions of the aircraft in order to allow personnel to have direct access to them. [13], [12], [27]
In [13], for ease of application, the used approach was derived considering non integral tanks. The LAPCAT MR2.4 has been designed for a modern configuration of the spaces with integral tanks, but for ease of handling, the model was developed for non integral tanks. The same approach was applied to the semplification of the shape of each of the bubbles provided.
The STRATOFLY project foresees the extension of the model for more complex shaped tanks as well as for integrated tanks.

4.1.2 Tank shape

Another fundamental choice to be made relates to the shape and geometry of the tank that best suits the size of the aircraft. Usually the choice falls between spherical and cylindrical shaped tanks of various lengths. As is well known, the first allow the minimum surface area for a given volume and minimizes the passive heat flux into the tanks. On the other hand, cylindrical tank shapes are easier to manufacture but have higher surface area to volume ratio, resulting in higher passive heat flux. In this case, cylindrical and elliptical tanks with hemispherical heads at each end have been considered. The shape of the tank is characterized by three dimensionless parameters obtained through the ratios of the geometric dimensions.

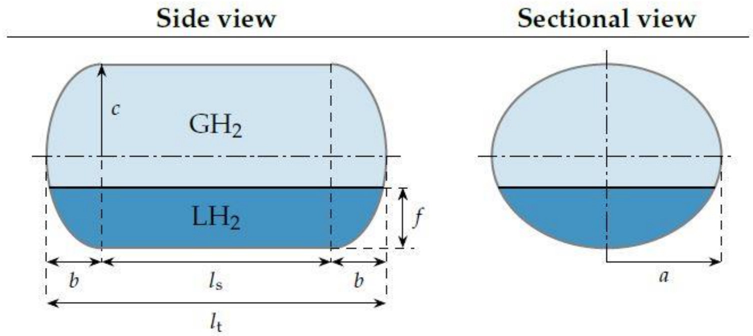

Figure 4.1 Geometric tank dimensions **[13]**

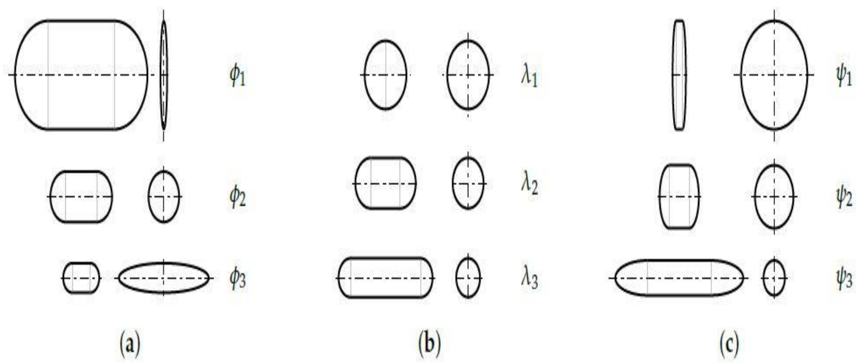

Figure 4.2 Geometries with different dimensionless parameters **[13]**
(a) $\boldsymbol{\phi = 0.1;\ 1.0;\ 5.0}$ ***(b)*** $\boldsymbol{\lambda = 0; 0.5; 0.75}$ ***(c)*** $\boldsymbol{\psi = 0.1; 1.0; 3.0}$

The dimensionless parameters are:

- ϕ, determines the shape of the shell $\phi = \frac{a}{c}$;
- ψ, represents the shape of the tank heads $\psi = \frac{b}{c}$;
- λ, defines the ratio of the shell length l_s and the overall tank length l_t, $\lambda = \frac{l_s}{l_t}$, with $l_t = l_s + 2b$. [13]

The parameters ϕ and ψ are the ratios between the ellipsoidal axes.
These measures enable a flexible tank design adaptable to predefined geometric constraints for a constant volume. If the tank shell is circular, $\phi = 1$. For hemispherical heads $\psi = 1$. Whereas $\lambda = 0$ when the shell length equals zero. The system is under-constrained when $\lambda = 1$, because b and therefore ψ equal zero. whereas $l_s \rightarrow \infty$, for λ =1. For this case study, $\lambda < 1$ is considered. Modifing the input a,b,c,l_s, l_t, this results in an infinite number of geometrical combinations. [13]

4.1.3 Tank insulation

The function of the insulation was previously discussed. The insulation can be installed at the inner or outer surface of the tank wall.
An inner insulation allows the temperature of the tank wall to remain close to the ambient temperature and at the same time provides better accessibility to the tank. However, this would continuously expose the insulation to hydrogen, crippling its thermal performance and effectiveness. Furthermore, the chosen material must resist permeation and embrittlement by hydrogen and also have low density.
External insulation may be more susceptible to mechanical damage and impervious to air. Maintaining the effectiveness of the insulation is most critical. Hence the advantages and disadvantages of the placement of the insulation must be considered. [13] , [12]

4.1.4 Tank structure

Two different types of tank structure may be analyzed: single wall construction with foam insulation and multilayer insulation (MLIs).
Multilayer insulation, generally used on spacecrafts, consists of a vacuum-jacketed system with layers of Mylar (or a similar type of material) of low emissivity and high reflectivity, separated by thin fiberglass sheets. The external container is capable of maintaining the vacuum pressure within the layers and minimizes the conductivity. The layers act as a radiation barrier keeping heat out of the tank. The main disadvantage of this solution is that if the vacuum is lost during
flight, the consequences could be catastrophic.

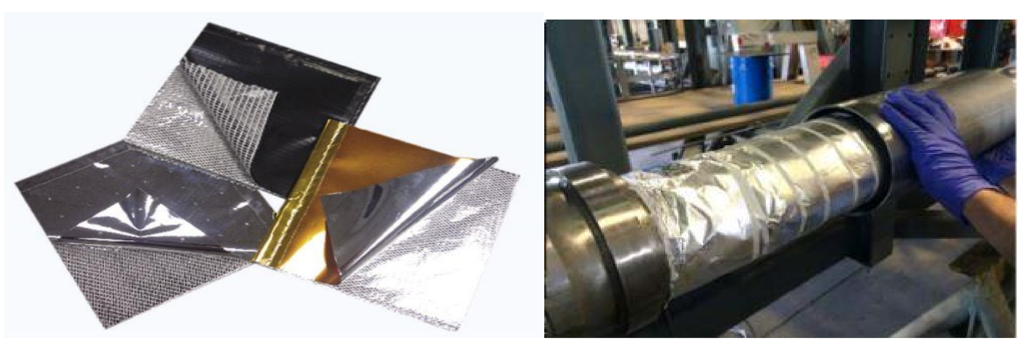

Figure 4.3 Multilayer Insulation

In the structure with foam insulation, a rigid closed cell foam is applied to the outside of the tank wall itself, taking up mechanical tank stresses. A thick, compressed, open cell layer that has been purged by a non- condensable gas such as helium is positioned on top of a closed cell foam layer to adapt dimensional changes. Sometimes, a multilayer sandwich, MAAMF vapour barrier, is applied on both sides of the flexible open cell. A thin metal layer may be placed on the outside of the foam to maintain its integrity and protect it from damage. The foam insulation is safer and more resistant than the multilayer insulation, but it has greater density and thermal conductivity. [26] [12]

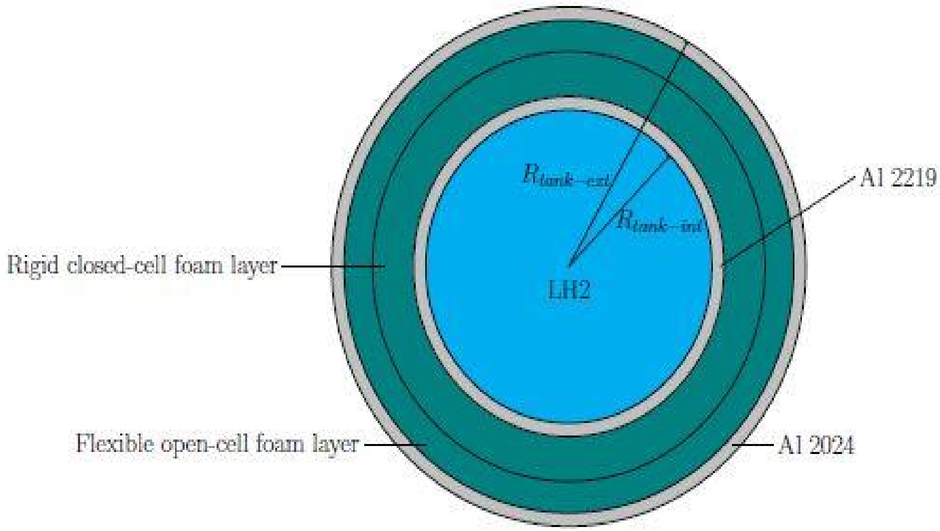

Figure 4.4 Single wall construction with foam insulation

4.2 Tank Materials

The design of a cryogenic tank requires a choice of materials resistant to hydrogen embrittlement, impermeable to gaseous hydrogen and capable of withstanding the temperature of liquid hydrogen. In the case of aerospace applications, preferably the material ought to be light and in parallel, have a high strength, stiffness and fracture toughness. However, today a material that simultaneously combines all these properties is not available.
The selection of the most suitable available material must be made both for tank wall material and insulation.

4.2.1 Tank wall materials

Numerous studies have been performed to compare different materials based on allowable stress, density, critical crack size and the low permeation to LH_2 and GH_2. Though strength and density dominate the design of tank wall, but other factors must also be considered. Due to low temperatures, many materials become brittle and lose their properties. For this reason, according to the criteria for damage tolerant design, fracture toughness becomes a determinant

index. In [28], polymer matrix composites (PMC), metal matrix composites (MMCs) and discontinuous reinforced metallic composites (DRXs) are examinated. The application of lightweight carbon fiber reinforced plastics is demonstrated to be critical to the success of the next generation missions, following the failure of the X-33 composite fuel tank that occurred in part due to the microcraking of the polymer matrix. For cryogenic applications, composite materials offer low density and higher strength and stiffness than metals, offering a potential weight saving. However, composite structures tend to have higher hydrogen permeation than metals and issues with different coefficients of thermal expansion. NASA and Marshall Space Flight Center are working on the use of polymer films that will act as a barrier to the permeation of hydrogen, but at the moment the effects and the exact properties are unknown. Due to limited knowledge and experience of the use of composite materials for cryogenic tanks, and associated high safety factors, it is expected that the monolithic metals will be used. This could significantly increase the mass of he tank wall.
In a study by NASA, the aluminium alloy 2219 was considered as the tank material as it fulfilled all requirements compared to others that were investigated. Pure aluminium metal, on the other hand, is one of the few metals with minimal susceptibility to hydrogen embrittlement. At a cryogenic temperature of 20 K, this material has a density of 2825 kg/m^3 and a limited stress of $\sigma_s = 172.4\ MPa$ under ultimate design conditions.

4.2.2 Insulation materials

In [28], state of the art and key design factors for insulation for cryogenic tanks are reviewed. To select the most promising insulation, several families of materials are evaluated, defining various performance indices. These indices take into account density ρ, thermal conductivity k, diffusivity a and thermal expansion coefficients α.
Figure 3.5 shows thermal conductivity versus thermal diffusivity and thermal conductivity versus thermal expansion coefficients for different materials. Figure 3.6 instead shows thermal conductivity versus density.

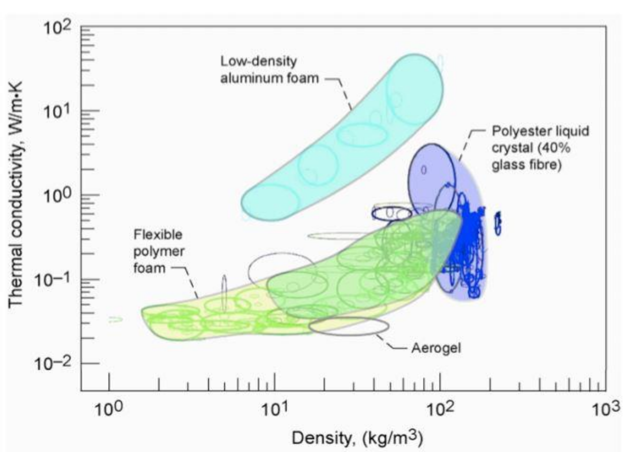

Figure 4.5 Thermal Conductivity vs Density

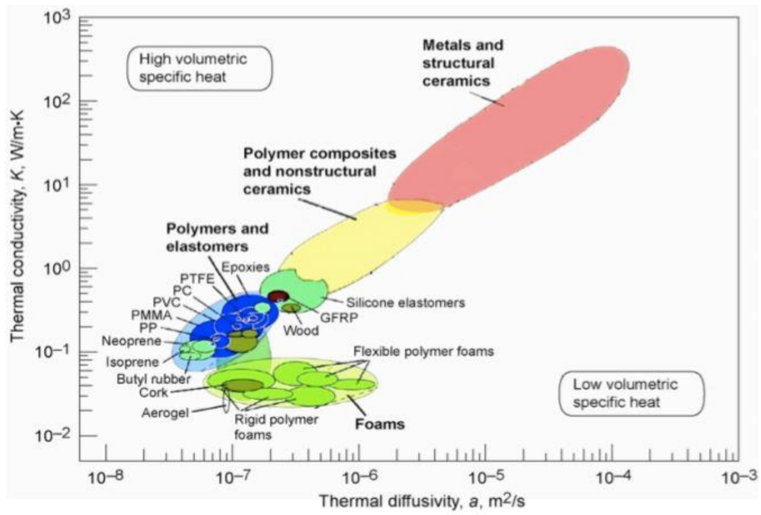

Figure 4.6 Thermal Properties of various engineering materials, based on Ashby. **[12] [28]**

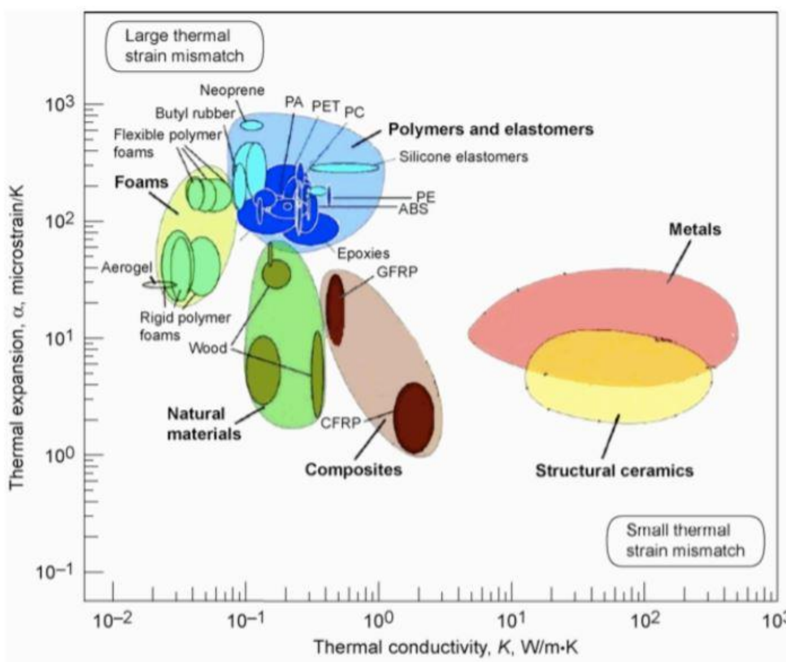

***Figure 4.7 Thermal conductivity versus thermal expansion coefficient for various materials, based on Ashby*. [12] [28]**

Scrutinizing thermal conductivity, density property and thermal expansion coefficients of numerous engineering materials, foams, aerogels and MLI systems identifies the most suitable characteristics for aerospace applications. This is validated by the use of these insulations systems in previous applications. Polymer foams and aerogels appear to be desirable for low density and ease of implementation. Aerogels have extremely low thermal conductivity but limited mechanical properties. MLI systems have a range of densities comparable with foams, and a thermal conductivity and radiation heat transfer that is much lower. However, they are

expensive to maintain and implement. Additionally, polymer foams and aerogels show a low thermal diffusivity. Insulations with rigid-cell foam for an integral and non-integral tank design are preferred options, due to performance and safety aspects. [13] [12]
The following table presents different insulation types and their conductivity and density:

Insulation Type	*Density* $[kg/m^3]$	*Thermal Conductivity [W/m K]*
Rigid closed cell polymethacrylimide	35.3	0.0096
Rigid open cell polyurethane	32.1	0.0112
Rigid closed cell polyvinalchloride	49.8	0.0046
Rigid closed cell polyurethane and chopped glass fiber	64.2	0.0064
Evacuated aluminum foil separated with fluffy glass mats	40	0.00016
Evacuated aluminum foil and glass paper laminate	120	0.000017
Evacuated silica powder	160	0.00017

Table 3 Tank insulation Properties **[26]**

The rigid polyurethane and the rohacell closed cell polymetacrylimide foams are the best candidates for insulation systems.

4.3 Sizing of the Tank

Using the information and data contained in the previous sections, in this part the design of LH_2 cryogenic tanks for hypersonic aircraft is explored. A set of compromises between geometrical, mechanical and thermal requirements is applied to obtain the full volume and the total mass estimation of the tanks system, based on the amount of fuel necessary for the mission and the available volume to accommodate the fuel system of the aircraft.
Figure 3.7 shows a flowchart which illustrates the input parameters, the results obtained as output and summarises the relations and procedures implemented.

The mechanical and thermal designs are introduced in the next subsections.

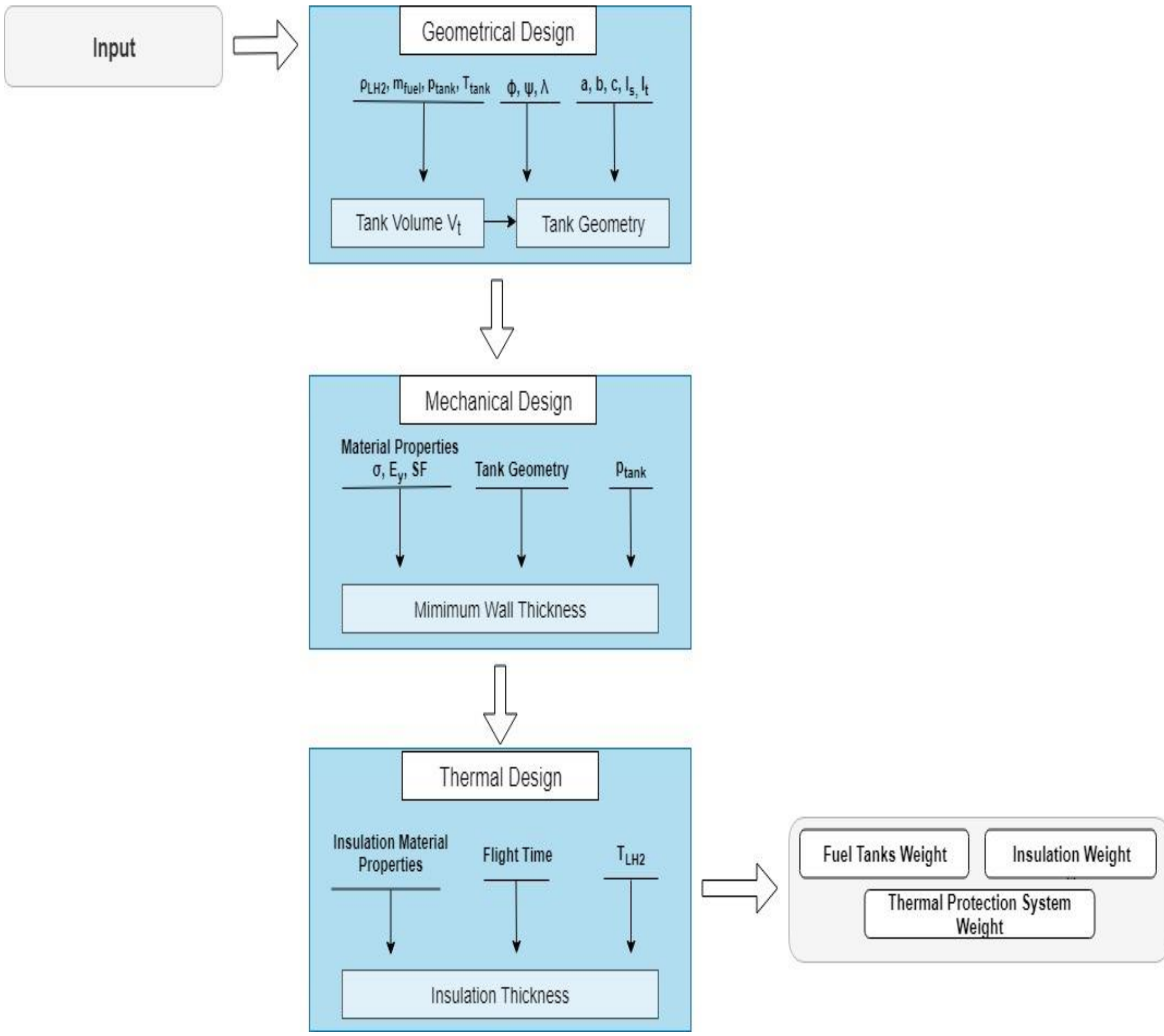

Figure 4.8 Flowchart of the design

4.3.1 Preliminary Design

As it is well known, hydrogen has a critical point identified by a pressure of 12.98 bar and a temperature of -239.91 °C. This means that in order to have liquid hydrogen, the temperature must be at least equal to or lower than the critical temperature. At atmospheric pressure hydrogen is liquid when it is at a temperature of approximately -253 °C. This information allows to deduce the initial state of the hydrogen stored inside the tank.

Pressure p [bar]	Temperature T [K]	Density ρ_{LH2} $[kg/m^3]$	Molecolar Weight $[kg/mol]$
1	20	70	$2 \cdot 1.016 \cdot 10^3$

Table 4 Hydrogen initial state

The Van Der Waal equation for real fluids has been implemented to obtain the minimun volume occupied (V) by the fluid, given the temperature and pressure conditions (T,p):

$$\left(p + a\frac{n^2}{V^2}\right)(V - nb) = n\,R\,T$$

With a, b, R typical constants of hydrogen, n numbers of moles. In this case:

$$a = 0.0247\ [J\ m^3\ /mol]$$
$$b = 2.65 \cdot 10^{-5}\ [m^3/mol]$$
$$R = 6.7\ [J/mol\ K]$$

The number of moles n is instead obtained by the ratio between the mass of fuel required for the mission and the molecular weight.
The Van Der Waal equation refers to the Andrews diagram on the transfer of state between substances, where:

- P, V, and T represent respectively the pressure, volume and temperature that characterize the physical state of the substance;
- T curves are isotherms;
- C is the critical point of the substance.

For isotherm curves with T< T_c there is the phenomenon of liquefaction of gas. For example, when T_2 is equal to -253 °C, points a and b correspond to atmospheric pressure. In the T_2 curve there are three parts: a section (d-a) where the substance is at the gaseous state, a horizontal section (a-b) where the volume decreases but the pressure remains constant and the substance is partly liquid and partly vapour and a section where the pressure increases rapidly from b. At point b the substance is completely liquid. The volume corresponding to point b is the value of interest. [29]

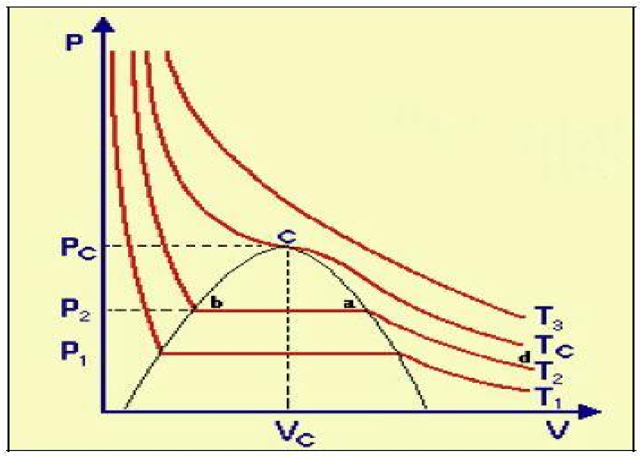

Figure 4.9 Andrews Diagram

Through the solving of this equation it is possible to obtain the volume occupied by liquid hydrogen. The equation allows the corresponding volume to be obtained even when the pressure and temperature are different.
Actually, the effective tank volume required can be found from the density of propellant at the maximum operating temperature. Knowing the propellant mass M_f $[kg]$ and the propellant density ρ_f $[kg/m^3]$, the propellant tank volume V_p $[m^3]$ can be found from the expression:

$$V_p = \frac{M_f}{\rho_f}$$

To maintain a constant pressure and provide space for boil off, an excess volume is estimated. The common margin is around 20% of the propellant volume at the beginning the design phase.
Clearly, this volume is compared to the available volume on the aircraft.

4.3.2 Geometrical and Mechanical Design

Once the volume of the propellant is known, iteratively it is possible to solve the following equation to obtain those that are the dimensions of the cylindrical tank (a, b, c, l_s):

$$V_p = \frac{4}{3}\,\pi\,a\,c\,b + \pi\,a\,c\,l_s$$

In this subsection, the three dimensionless parameters (ϕ, ψ, λ) which characterise the shape of the tank can be used.
However, in this specific case study, the size of the tanks was known in advance. At this point, then, what has been obtained is the total true volume occupied by the tanks, given the sizes.

In aircraft applications, it is important to minimize weight. Due to the high density of the tank material selected, the minimum wall thickness which makes it possible to satisfy the official regulation can be derived from the follow relation:

$$s_w = \frac{p_{max}\, d_i/2}{v\,(2\frac{K}{SF} - p_{max})}$$

Where

K is the limited stress of the material $[MPa]$

SF is the safety factor (1.5)

p_{max} is the maximum pressure inside the tank $[MPa]$

v is the weld efficiency (0.07-0.85)

d_i is the equivalent diameter $[m]$

From the wall thickness s_w and the density of the tank wall material ρ_t, the mass of the tank $m_t[kg]$ can be calculated:

$$m_t = \rho \cdot \left[\frac{4}{3}\,\pi\,(a + s_w)(c + s_w)(b + s_w) + \pi\,(a + s_w)(c + s_w)\,l_s - V_T\right]$$

Through the use of this expression it is possible to obtain the mass of each tank present on the aircraft. The total fuel tank mass is given by the sum of each single tank mass.

Case Study

A Matlab tool was developed to measure cryogenic tanks of LH_2 fueled hypersonic STRATOFLY aircraft, using the relationship reported above.

Simple cylindrical tanks, wich start and end with equal cross sections, are considered.

The table 5 listed input parameters for the analysis:

	BCAT	BCFT	BSAT	BSFT	WT
Effective fuel volume available $[m^3]$	130	557	406	233	1273
Equivalent length, l_t[m]	21	44	27	29	58
Cross Section Area, A $[m^2]$	7.2	12.9	7.7	4.1	11.8
Hydraulic Diameter $[m]$	2	3.2	2.1	1.7	2.2

Ellipticity $\phi = c/a$	7	4	7	5	10

Table 5 Tanks Characteristics [16]

Some parameters can be entered from the keyboard. For example, the amount of fuel needed for the mission, the number of tanks or the properties of the material to use.
Vectors with dimensions equal to the number of tanks have been created. If the number of tanks is different, it is necessary to change the dimensions of the vectors.
The created Matlab Tool, implenting the equations and using input parameters, allowed the following results to be obtained:

Necessary Fuel for the mission [kg]	182000
Available Volume [m^3]	3000
Fuel Volume [m^3]	2893.348
Effective Fuel Volume available [m^3]	2600
Number of tanks	8
Total volume of tanks [m^3]	2792.8
Al 2219 density [kg/m^3]	2825
Al 2219 limited stress [MPa]	172.4
Minimun Thickness BCAT [mm]	1.230
Minimum Thickness BCFT [mm]	1.967
Minimum Thickness BSAT [mm]	1.291
Minimum thickness BSFT [mm]	1.045
Minimum thickness WT [mm]	1.353
Total Tanks Mass [kg]	**14549**

Table 6 Results for Lapcat MR2 tanks configuration

The total mass obtained is obviously a first estimate that can be made during the preliminary design phase of the propellant system and can be considered as a starting point for the steps that follow. This value affects the total weight of the aircraft. Notice that this is the tank mass only. The mass of the fuel is not taken into account. More detailed evaluations may also

suggest a change in the subdivision of the volume of propellant and consequently a change in the volumes and weights of the tanks.
The next step is the thermal design phase.

4.3.3 Thermal Design

One of the major issues during the preliminary design of cryogenic tanks is the thermal losses due to the huge temperature gradient between the fluid and the surrounding environment. The objective of this section is to design an efficient thermic insulation to prevent excessive boil off or ice forming. A precise thermal analysis is thus important.
The model used to estimate the correct passive insulation tanks is based on the engineering method of Ardema and it is valid for both wetted inside by the fuel or dry tank. The closed analytical formulation assumes a (quasi)-steady state analysis for the insulation thickness calculation.
For a wetted tank the needed insulation thickness is :

$$L_{ss_{wet}} = \left[\frac{\rho_F\ \kappa_{ins}\ t_{fl}(T_{sur} - T_F)}{h_{fg}\rho_{ins}}\right]^{\frac{1}{2}}$$

For a dry tank:

$$L_{ss_{dry}} = \frac{\kappa_{ins} t_{fl}}{[C_M L_M \rho_M \ln[(T_{sur} - T_F)/\ (T_{sur} - T_M)]]}$$

Where,

$\rho_M, \rho_{ins}\ and\ \rho_F$ are respectively, the density of the material, insulation and and fuel;
$T_{sur}, T_F\ and\ T_M$ are the external surface temperatures of the tank, the fuel tank temperature and maximum tank material design temperature;
C_M is the heat capacity of the tank material;
L_M is the tank wall thickness;
κ_{ins} is the heat conductivity of the the insulation material;
h_{fg} is the heat of vaporitation of the fuel;
t_{fl} is the exposure time.

The exposure time of each tank depends on flight conditions and flight phases. These factors, in combination with the corrisponding varying equilibrium, make it difficult to calculate insulation thicknesses correctly, overstating the thermal proctection.
Using this steady state approximation, it can be demonstrated that the thicknesses are overestimated. The overestimation for wet tank thickness is 11.7% , and for the dry tank

thickness it is 35%, compared to the thickness calculated by means of a classic analysis of transient heat transfer. In this analysis these percentages have been taken into account.
This formululation also suggests a relationship for calculating the weight of insulation per unit surface W_{ss}, considering half of the tankage surface area to be wetted and the other half area to be dry:

$$W_{ss} = \frac{0.894\ \rho_{ins}\ L_{ss_{wet}} + 0.741\ \rho_{ins} L_{ss_{dry}}}{2}$$

At the same time, an equation to estimate the amount of boil off per unit of wetted surface is suggested:

$$W_{ss\_boiloff} = \frac{0.894\ \rho_{ins} L_{ss_{wet}}}{2}$$

Optimizing the calculation of the insulation thickness makes it possible to estimate the correct amount of boil off.
The final proposal is for a global TPS weight correlation which allow the total weight of the thermal protection system to be calculated:

$$W_{TPS} = A_B[U_{CP} + U_{CST} + K_{TPS} U_{ins}]$$

Where
U_{CP} is the unit mass of the cover panels;
U_{CST} is the mass of stand-offs and other items;
K_{TPS} is a non optimum factor taken.

Case Study
Even at this design stage, the created Matlab tool implements the above equations and applies them to the starting configuration of the STRATOFLY vehicle.
For each tank, the required insulation thicknesses and insulation weight has been calculated.
The total weight of the insulation system is the sum of the individual insulation weights of each tank.
Here, too, additional input parameters have been introduced and the results obtained from the previous sections, such as the thicknessess of the tanks walls or the tank wall material data, have been used.
Because the insulation weight of each individual tank is given per unit area, it is necessary to multiply the values by the corresponding exterior interface areas. For this reason an evaluation

of the surface areas interfacing between tanks is made, followed by the that of the interface between tanks and the passenger cabin and the landing gear wells.The following table shows the values in matrix form. The total outer surface of each tank is the sum of the corresponding row plus the corresponding column.

	Passenger cabin	**Body Center Aft Tank**	**Body Center Forward Tank**	**Body Side Aft Tank**	**Body Side Forward Tank**	**Wing Tank**	**Landing Gear Wells**	**Exterior**
Passenger Cabin	x	55.8	154.9	0.0	0.0	365.0	27.3	1103.6
Body Center Aft Tank	x	x	0.0	0.0	0.0	0.0	34.0	230.0
Body Center Forward Tank	x	x	x	0.0	0.0	0.0	66.9	516.9
Body Side Aft Tank	x	x	x	x	0.0	168.0	0.0	668.1
Body Side Forward Tank	x	x	x	x	x	0.0	0.0	572
Wing Tank	x	x	x	x	x	x	0.0	1956.1
Landign Gear Wells	x	x	x	x	x	x	x	35.8
Exterior	x	x	x	x	x	x	x	x

Table 7 Tank surface Areas

In actual fact, the surfaces interfacing with the passenger cabin were ultimately not included in calculations due to this aspect belonging to the Environmetal, Control and Life Support system. The same is applied to the landing gear wells.
The insulation used material is the Rohacell closed-cell foam, which possesses a density of 35.24 kg/m^3 and a thermal conductivity approximately of 0.035 $\frac{W}{mK}$.
The following Table 8 summarises respective input data:

	Body Center Aft Tank	Body Center Forward Tank	Body Side Aft Tank	Body Side Forward Tank	Wing Tank
Flight Time $[s]$	7200	7200	1500	1500	3700
Hydrogen Density $[kg/m^3]$	70	70	70	70	70
Heat of vaporization hydrogen $[MJ/m^3]$	35.7	35.7	35.7	35.7	35.7
Insulation Thermal Conductivity $[W\ /m\ K]$	0.035	0.035	0.035	0.035	0.035
Insulation Density $[kg/m^3]$	35.24	35.24	35.24	35.24	35.24
Wet Surface Temperature $[K]$	700	700	300	300	450
Dry Surface Temperature [K]	800	800	301	301	450
Hydrogen Temperature $[K]$	20	20	20	20	20
Tank Wall Material Density $[kg/m^3]$	2825	2825	2825	2825	2825
Tank Wall Thickness $[m]$	0.0012	0.002	0.0013	0.0010	0.0014
Tank Material Heat Capacity [J/ kg K]	864	864	864	864	864

Table 8 Input Parameters

The insulation thicknesses and weights obtained are:

Body Center Aft Tank	
Wetted Insulation Thickness [m]	0.0974
Dry Insulation Thickness [m]	0.0878
Average Insulation Thickness [m]	0.0926
Insulation Weight [kg]	619.65

Table 9 BCAT Insulation

Body Center Forward Tank	
Wetted Insulation Thickness [m]	0.0974

Dry Insulation Thickness [m]	0.0549
Average Insulation Thickness [m]	0.0762
Insulation Weight [kg]	1169.21

Table 10 BCFT Insulation

Body Side Aft Tank	
Wetted Insulation Thickness [m]	0.0285
Dry Insulation Thickness [m]	0.0029
Average Insulation Thickness [m]	0.0157
Insulation Weight [kg]	409.92

Table 11 BSAT Insulation

Body Side Forward Tank	
Wetted Insulation Thickness [m]	0.0285
Dry Insulation Thickness [m]	0.0036
Average Insulation Thickness [m]	0.0161
Insulation Weight [kg]	285.95

Table 12 BSFT Insulation

Wing Tank	
Wetted Insulation Thickness [m]	0.0285
Dry Insulation Thickness [m]	0.0036
Average Insulation Thickness [m]	0.0161
Insulation Weight [kg]	2374.42

Table 13 WT Insulation

Total Insulation Weight [kg]	**7929.46**

Regarding the amount of boil off fuel, the following values resulted:

	BCAT	BCFT	BSAT	BSFT	WT
Boil Off Mass [kg]	354.57	796.86	377.52	258.54	1866.58

Table 14 Boil Off Mass

Total Boil Off Weight [kg]	**6156.738**

Table 15 Total Boil Off Mass

It was decided to use superalloys with unit mass of 4.33 kg/m^2 as the material for the cover panels, as they have a limit temperature of 1255 °K. Using ceramic tile cover panels could result in a weight saving. The weight of stand offs and other items is estimated at 1.16 kg/m^2. It is possible to summarize the weights of the cover panels and stand offs as per data in Table 16:

	BCAT	BCFT	BSAT	BSFT	WT
Covers Mass [kg]	995.90	2238.17	3620.31	2479.35	9196
Stand offs Mass [kg]	266.8	599.604	969.87	664.21	2463.84

Table 16 Covers and Stand Offs Mass

At this point, adding together the total weight of each component allows the weight of the entire thermal protection system to be determined:

Total Insulation Weight [kg]	7929.46
Total Cover Panels Weight [kg]	33827.25
Total Stand offs Weight [kg]	9062.27

Total TPS Weight [kg]	**50818**

Table 17 Thermal Protection System Weight

The total boil off mass summed from all tanks is estimated at 6.15 tons. This value may decrease if a different thermal analysis model is used.

By optimizing the design process, it is also possible to achieve a reduction in the mass of the thermal protection system thus significantly affecting the total weight of the aircraft.

In reality, this process could be part of the design of another aircraft subsystem, such as the thermal control system or the thermal and energy mangement system.

5 PROPELLANT SUBSYSTEM DESIGN

This chapter analyses the propellant subsystem of the starting configuration of the STRATOFLY vehicle. In particular, its architecture is explained and then modeled on the Matlab-Simulink environment. In the first part, the considered case study and the hypotheses are presented. The second part focusses on the modeling of the system in the Matlab environment, using the Simscape library. The model created ad hoc allows the evaluation of the mechanisms for emptying the tanks and how these can affect the preliminary movements of the center of gravity of the aircraft to ensure its stability.

The major function of the fuel system is to supply fuel to the engines at any flight level, condition and manoeuver. The propellant subsystem of an aircraft is a series of interconnections between various parts and components of appreciable complexity.

The propellant system functions can be divided into primary functions, secondary functions and accessory functions.

Primary functions are those functions for which the system is specifically designed:

- To contain propellant;
- To feed engines.

Accessory functions are the functions that enable the primary ones:

- Refueling or Defuelling;
- To allow emergency drain;
- Fuel pouring;

Secondary Functions are not related to the primary functions but can be performed by the subsystem in some specific applications:

- To control CoG position;
- To provide heat sink;
- To cool down propulsion subsystem;
- To provide insulation.

Among the main components that perform these functions are:

1. the tanks, that deal with some of the primary and secondary functions, such as containing the propellant or providing heat sink;
2. feeding, transfer and refuelling lines;
3. pumps and valves to move propellant from tank to engines or between tanks or for emergency drain.

In addition, tanks can be subdivided into:

Primary tanks: these feed the engine directly. The propellant is pumped from these tanks into the feeding line, to reach the combustion chamber.

Auxiliary tanks: these contain propellant that is transferred to the primary tanks before passing into the feeding lines. These tanks are the the first ones to be emptied. They have an important role in definig the weight and the balance of the aircraft.

During the design phase, it is therefore necessary to correctly define the architecture of the tanks and their location, and especially the strategy of emptying. At the same time, it is necessary to identify suitable propellant pumps and valves, which means examining the pressures and the volumetric mass flow rate that can be guaranteed, especially in the case of hypersonic applications due to the characteristics of the fluids.
The final definition of the architecture of the propellant subsystem has not yet been identified. Further to this, the division into primary and secondary tanks, as well as the actual emptying strategy have not been determined.

5.1 Propellant Subsystem Architecture

The first thing that is necessary is the identification of the most suitable architecture.
Each tank must be positioned in such a way as to meet the design requirements and fulfil the objectives of the mission. In this case, the number of aircratft tanks of different shapes is equal to eight and they are: wing tanks (WT), body side aft tanks (BSAT), body side forward tanks (BSFT), body center aft tank (BCAT) and body center forward tanks (BCFT).
The side tanks supply the engines during the take-off and acceleration phases, the wing tanks contribute to supply the engines both during take-off and during the ascent and acceleration phases. In addition, part of the fuel is also used during the cruise phase, as is the fuel present in the central front and aft tanks.

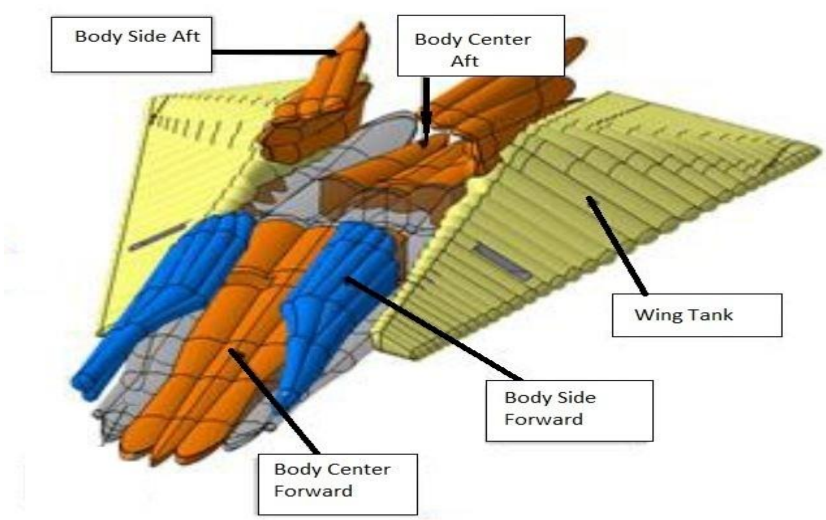

Figure 5.1 Tanks Location

For convenience, the propellant system can be divided into a series of subsystems, consisting of the tank itself, transfer or feed pumps and valves. Each tank has a specific volume containing a defined amount of liquid hydrogen. Any reserves for emergency situations are always taken into account. Each subsystem is linked to another subsystem according to a definite hierarchy. A fundamental step in the designation of the architecture is the definition of the main and secondary tanks. The identification of these facilitates the design of the propellant system and the modelling within the simulation program.

In this work, the Body Center Aft and Body Center Forward tanks have been chosen as the main tanks. They will directly power the engines. All other tanks are connected to them and therefore represent the secondary tanks. In particular, the wing tanks and the side aft tanks were selected as auxiliary tanks of the central aft tank. The forward side tanks on the other hand, were chosen as auxiliary tanks for the forward central tank. In reality, the fuel is first pumped from the side aft tanks to the wing tanks, and then from the wing tanks to the central aft tank. Previous study have shown that moving fuel from one tank to another can significantly influence the stability of the aircraft and the position of the centre of gravity during all phases of the mission. Therefore, the choice of main and secondary tanks has been made on the basis of this knowledge and the resulting constraints. In general, during the acceleration phase through the various Mach values, the fuel is pumped out of the front tanks towards the aft. This results in a rearward shift of the CoG. At the end of the cruise during deceleration, the fuel is pushed forward, thus moving the CoG forward again while the center of the lift moves rearward. In this case, the aim is to keep these shift to a minimum. Hence, the calculation of the centre of gravity of the aircraft is influenced by the position of the centre of gravity of the individual tanks, which continues to change as the tank empties.

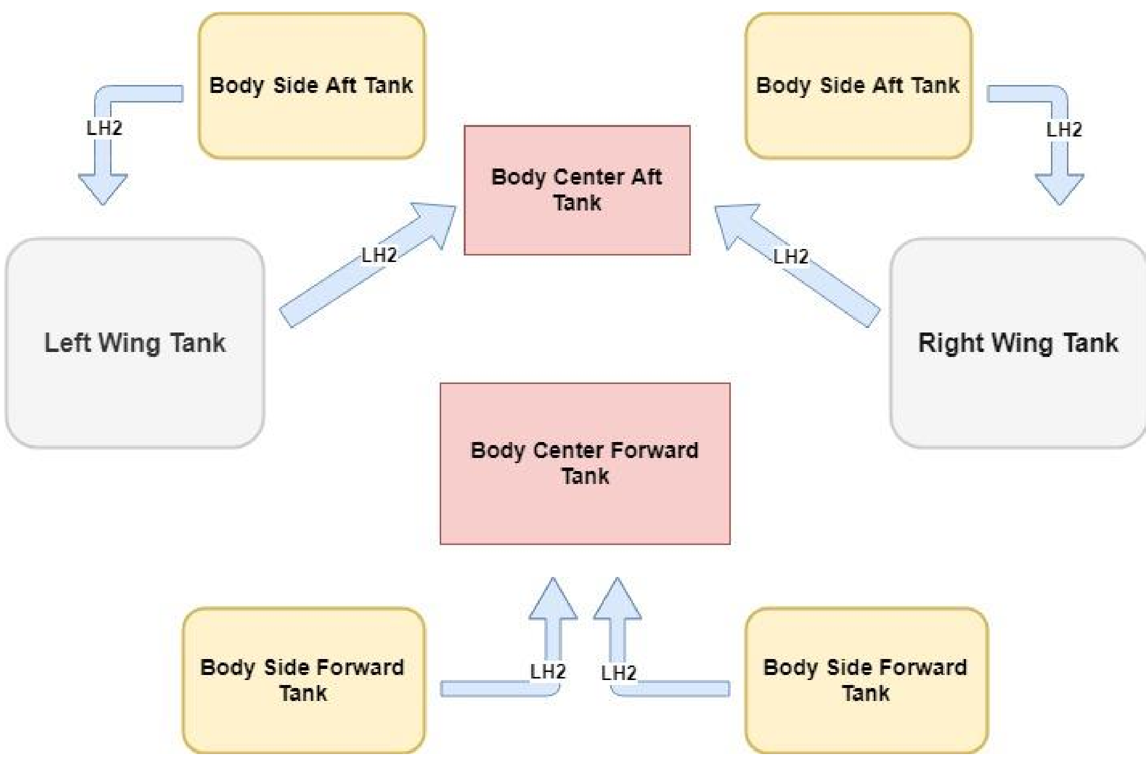

Figure 5.2 Tanks hierarchy

The biggest difficulty is to derive a law for emptying each of tank, because of the unconventional shape. For cylindrical tanks, it is sufficient to simply calculate the level of liquid present in the tank through trigonometric equations based on the geometry of the tank itself.
Based on the model created in the Matlab-Simulink environment and the Simscape library, the aim of this project has been to derive a curve to show the trend of changes of the liquid level in the tanks.
In the next section, the hypotheses and the steps that led to the creation of the model will be explored.

5.2 Subsystem Simulation in Matlab-Simulink environment

The library of Matlab-Simulink program used to create the model of the propellant subsystem in question is called Simscape.
Simscape enables the creation of models and simulates physical systems, based on physical connections and integrating the components with blocks diagrams. It models systems such as electric motors, hydraulic actuators and refrigeration systems by assembling key components into a diagram. Physical block modeling covers more than 10 physical domains, including mechanical, electrical, hydraulic and biphase fluids. Simscape products offer an efficient way to compose the mathematical model of the physical system, allowing you to vary the design of the system without deriving or implementing the equations at the system level.
The Simscape library can be divided in product families, covering a wide range of applications:

- Simscape Driveline
- Simscape Electrical
- Simscape Fluids
- Simscape Multibody

Mechanical, electrical, thermal and other physical systems can be integrated into a model using components from the Simscape family of products.
Simscape Fluids provides components for modeling and simulating fluid systems. It includes hydraulic pumps, valves, actuators, pipelines, and heat exchangers. It also enables the development of fuel supply systems. For this reason, the product family used in this investigation is that of fluids. In turn, the products of the Simscape Fluids family can be divided into subcategories, according to the type of fluid: isothermal liquid, gas, thermal liquid, twophase fluid. Every component is specialized for modeling fluid networks in the specific domain. [30]
Before starting the creation of the model, the domain of two-phase fluid was the chosen category, because as has been previously discussed, liquid hydrogen is subject to the phenomenon of boil off. A fraction of this gaseous fuel provides cooling to the cabin and is used to cool down the propulsion plant. It is then expanded through a turbine to provide

mechanical power. Hence, using this category, a model that respected the physics of the entire system could be created.
The choice then fell back into the thermal liquid, due to some unknown liquid properties required by the program. As the creation of the model proceeded, it also became evident that in this case that the thermal liquid domain was not suitable for the intended purpose. Ultimately, it was decided to create the propellant system, considering it as a hydraulic network with an isothermal fluid.
First, it was necessary to find a way to represent the engines. Simscape already has aircraft engine models such as the turbofan engine, but in this case the engines present on the hypersonic aircraft are very different. The aircraft's engines are Air Turbo Rockets and Dual Mode Ramjet.

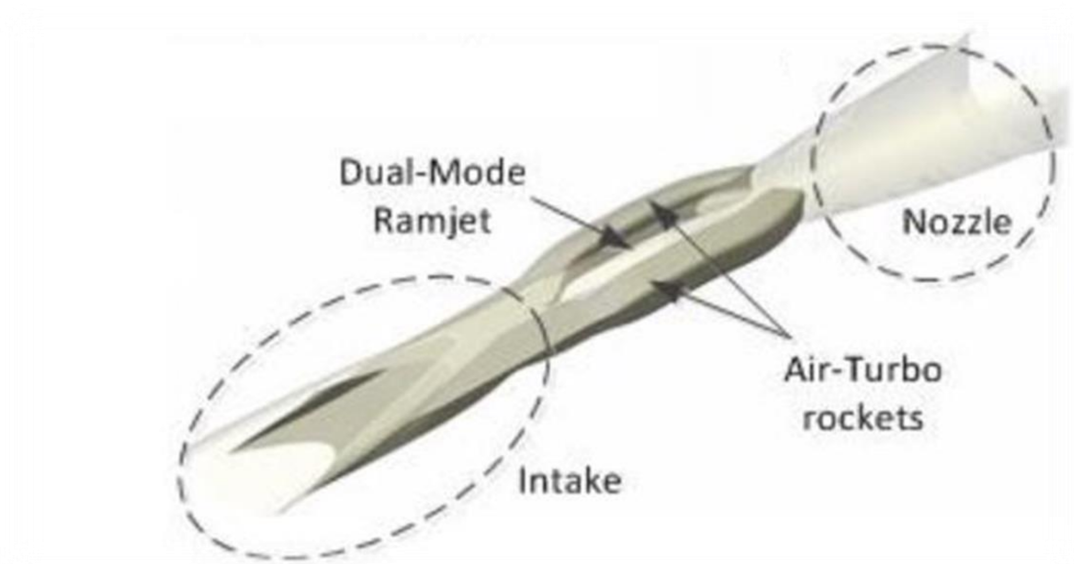

Figure 5.3 Propulsion Plant

Because Simscape does not provide blocks that model the physics of engines of this type, it was decided to model the aircraft's engines using a typical aircraft centrifugal pump connected to an ideal angular velocity source and to a hydraulic reference.

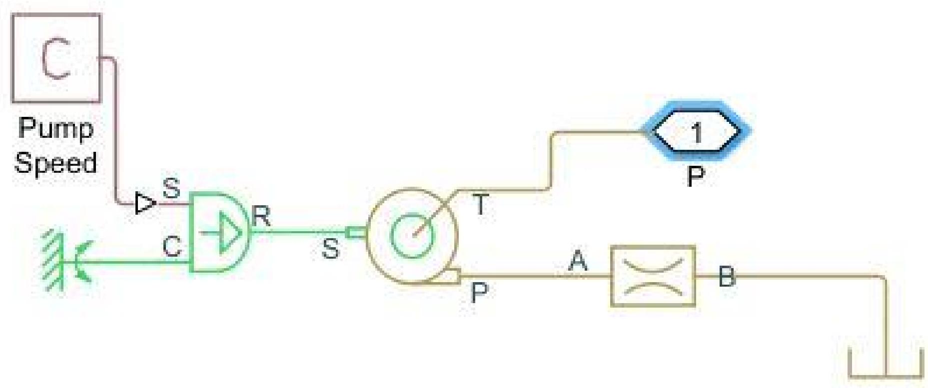

Figure 5.4 Engine Block

The source is ideal in a sense that it is assumed to be powerful enough to maintain a specified velocity regardless of the torque exerted on the system. Block connections R and C are mechanical rotational conserving ports. Port S is a physical signal port, through which the control signal that drives the source is applied. The Pump Speed block creates a physical signal constant. The hydraulic reference block represents a connection to atmosphere. [30]
To ensure that the centrifugal pump correctly represented the engines, the data of the fuel pump present on the aircraft were used as input parameters.
In particular, the following carriers were built and used:

- Pump delivery vector for pressure differential;
- Pressure differential across pump vector;
- Brake power vector.

Component	**Temperature [K]**		**Pressure [bar]**		**Mass Flow**	**Power**
	In	Out	In	Out	[kg/s]	[MW]
Fuel Pump	20	[26, 28]	1	60	[0, 100]	[1,15]

Table 18 Fuel Pump Operation Range **[31]**

The pumping power is proportional to the amount of liquid hydrogen which needs to be injected within the engines throughout the trajectory.
At this point, a block has been inserted that represents an ideal mechanical energy source in a hydraulic network and can maintain a controlled mass flow rate. The source does not generate

any losses due to friction. The mass flow rate is set by the physical signal port M. A positive mass flow rate causes liquid to flow from port T to port P. [30] The physical signal was generated through a flow rate profile.

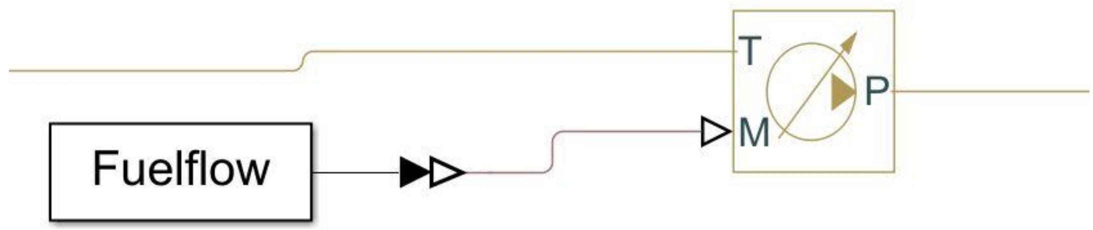

Figure 5.5 Flow Rate Source

Figure 4.7 was used to create the profile and by approximating the purple curve with different slope lines depending on the phase of the mission. It was made for a mission time of 7000 seconds. The profile is provided through a Matlab script, and therefore from workspace. A Simulink-PS converter converts the unitless Simulink input signal to a physical signal.

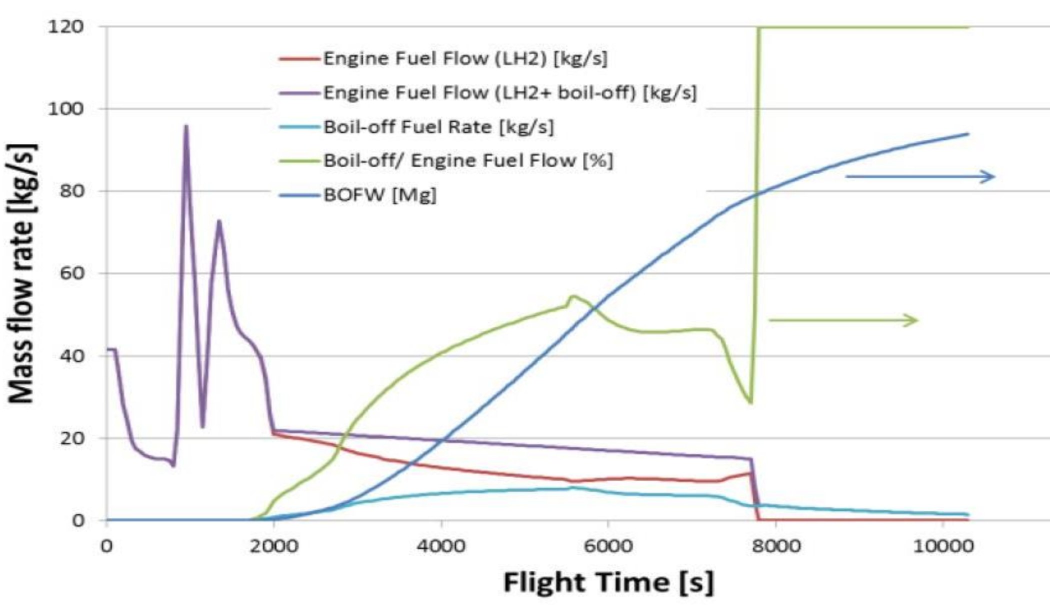

Figure 5.6 Flow Rate Profile [31]

When creating a model that represents a hydraulic network, the properties of the fluid must be assigned for all the components assembled in a particular loop through the Custom Hydraulic Fluid block. The block is considered as part of the loop if it is connected to at least one of the loop components. If no Hydraulic Fluid block is connected to the loop, the default properties of the Custom Hydraulic Fluid block are assigned. [30] Since liquid hydrogen is the fluid in the network of the propellant system that has been modelled, its properties have been assigned through this block. The input parameters required in this block are:

- Fluid density;
- Kinematic viscosity;
- Relative amount of trapped air.

In general a block that defines the solver settings to be used for the simulation is always connected to the Custom Hydraulic Fluid block.

Figure 5.7 Custum Hydraulic Fluid block

At this point it is possible to switch to the modelling of the subsystems of the propellant system. Again, eight subsystems have been created corresponding to the eight tanks on the aircraft. It is necessary to distinguish the subsystems related to the main tanks, as they have been modelled differently.

Following the hierarchy previously described, the secondary Body Side Aft tank was the first modelled tank. Its subsystem consists of the tank, a two-way directional valve, two centrifugal pumps and two check valves.

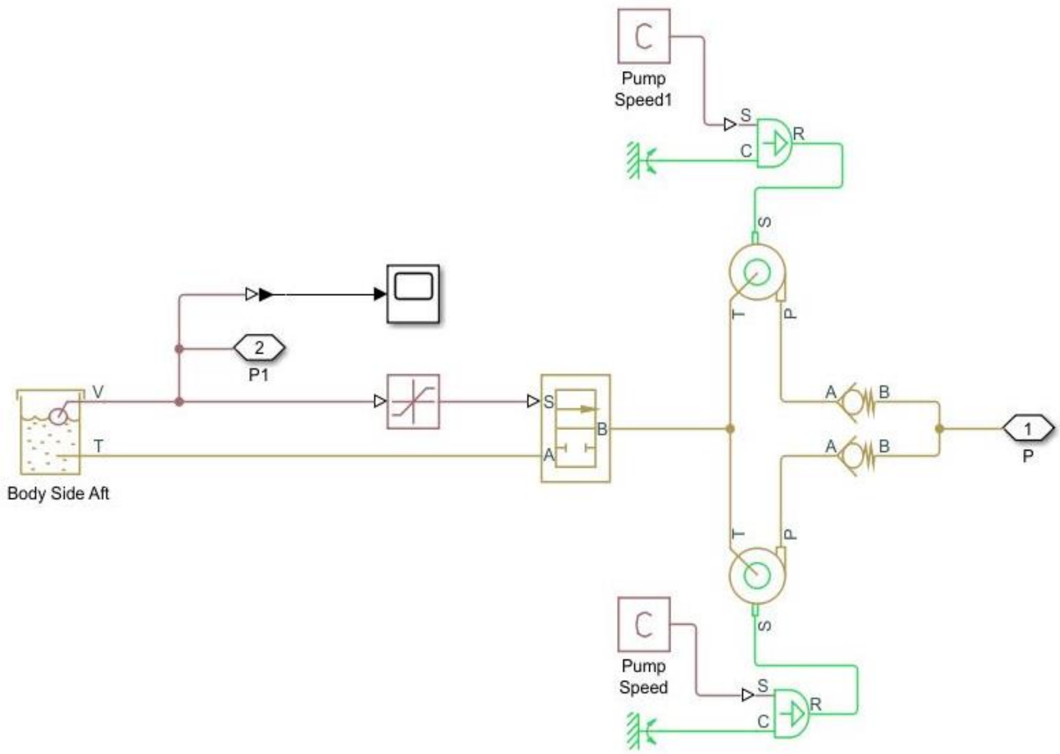

Figure 5.8 Body Side Aft Tank Scheme

The tank block models a storage tank with a constant pressurization and a selectable number of inlets. In this case, a number of inputs equal to one have been selected. The block accounts for the fluid level change caused by the volume variation and pressure loss. Port T is the hydraulic conserving port associated with the tank outlet. Physical signal output V reports the fluid volume in the tank. The scope block shows volume changes. It requires as input parameters:

- Pressurization;
- Tank cross section area;
- Pressure loss coefficient;
- Acceleration due to gravity;
- Minimum level of fluid;
- Beginning value of fluid volume and level.

This is the only case in which the pressurization parameter has been set to 5 bar and not 1 bar, to comply with the physics of the system.

The 2-Way Directional Valve block models a two-way directional valve in a hydraulic network. Port A and B are hydraulic conserving ports associated with the inlet and outlet. The control member displacement is set by a physical signal input S. It requires as input parameters:

- Valve passage maximum area;

- Valve maximum opening;
- Initial Opening;
- Leakage Area;
- Flow Discharge Coefficient;
- Laminar Flow Pressure Ratio. [30]

In this case, centrifugal pumps are transfer pumps, as this tank is secondary. The input parameters entered are based on the technical data of a centrifugal pump typically used in space rockets dealing with liquid hydrogen.

The check valve block represents a hydraulic check valve as a data sheet-based model. The purpose of a check valve is to permit flow in one direction and block it in the opposite direction. Connections A and B are hydraulic conserving ports associated with the valve inlet and outlet, respectively. The block positive direction is from port A to port B. The input parameters are:

- Maximum passage area;
- Cracking pressure;
- Maximum opening pressure;
- Flow discharge coefficient;
- Leakage area;
- Critical Reynolds number. [30]

As can be seen from the diagram, a saturation block has also been inserted. The flow through the two-way valve is closed when the tank reaches the zero liquid level limit. For redundancy and in terms of safety, the number of transfer pumps and check valves is equal to two. The same scheme was used to model the Left Body Side Aft reservoir, for symmetry of the aircraft and to avoid imbalance.

The second modelled subsystem is the one related to the Wing Tank.

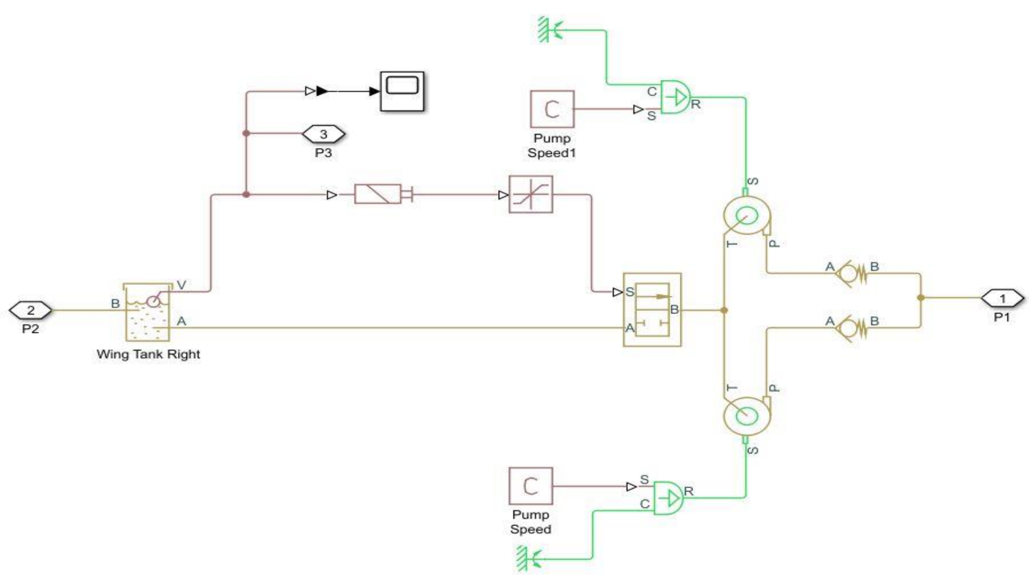

Figure 5.9 Wing Tank Scheme

It can be seen that the model is the same as in the previous case. However, the wing tank has two inlets. The reason is that according to the tank hierarchy, fuel is transferred from the body side aft tank to the wing tank before reaching the main tank and then the engines.
In addition to the saturation block, there is a 2-position valve actuator. The block is a data sheet-based model of an actuator that drives directional valves and assumes two positions: extended and retracted. The actuator is activated if the input signal crosses 50% of its nominal value. [30]
The same scheme was used to model the Left Wing reservoir.
At this point, it is possible to model the central aft subsystem, to which the two previous ones are connected. The Body Center Aft Tank is a primary tank and for this reason it has two inlet ports A and B and one output port C.
The scheme is similar to the previous ones. However, there are two directional two-way valves. These regulate the inlet of the flow coming from the wing tanks, in order to guarantee a correct flow rate and no imbalance.
On the output line there is the Hydraulic Flow Rate Sensor which measures the flow rate in a hydraulic network. Physical signal outputs Q and M report the liquid volumetric flow rate and mass flow rate, respectively, through the sensor. During the modelling phase, this sensor allowed the valves and pumps to be sized correctly so that the flow rate required by the motors was the exact one.
The Constant block that emits the constant specified by the "Constant value" parameter has also been inserted to allow the two directional valves to have a suitable S input signal.

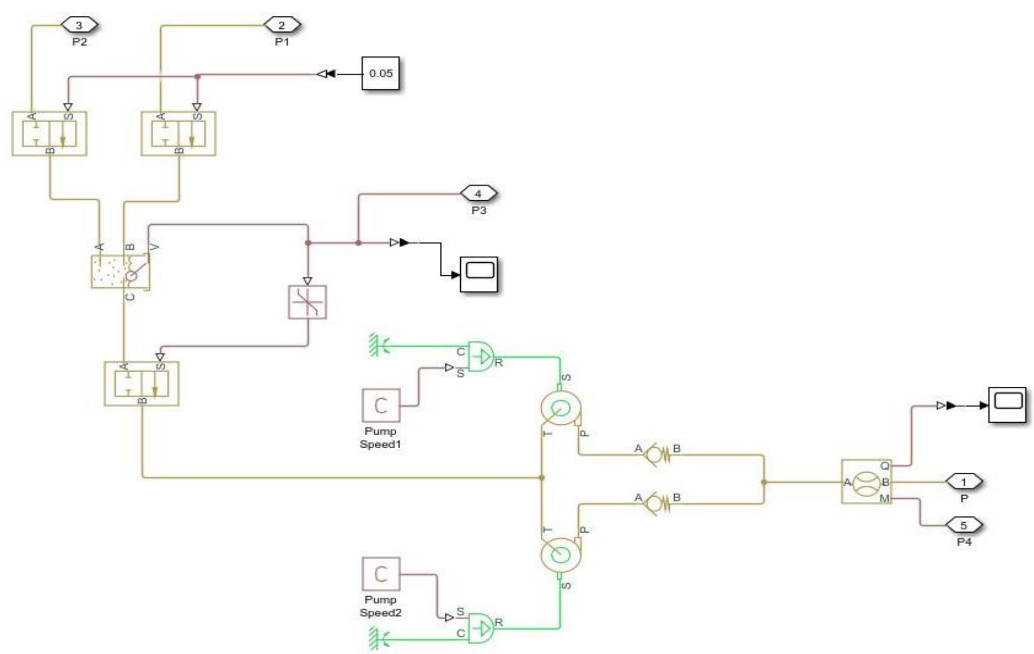

Figure 5.10 Body Center Aft Tank Scheme

Following the same reasoning as previously used, the schemes of the auxiliary tanks Body Side Forward and the primary tank Body Center Forward were created.
The layout of the Body Side Forward Tank subsystem is as follows:

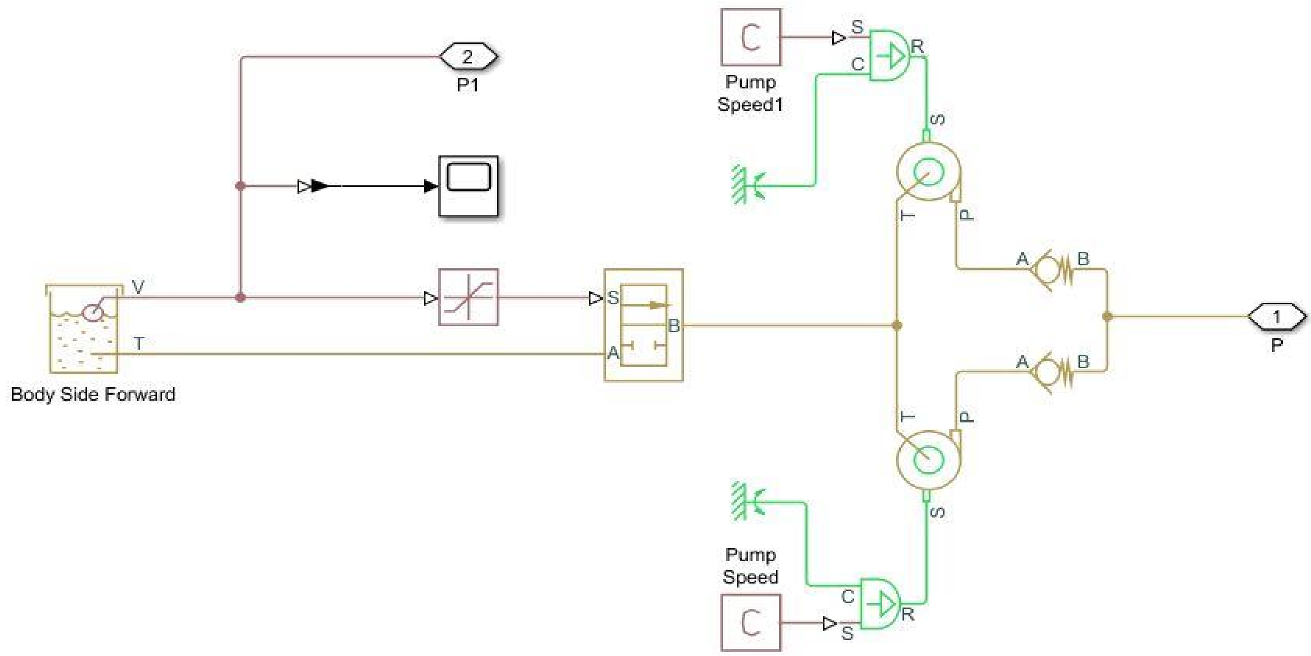

Figure 5.11 Body Side Forward Tank Scheme

As it can be seen, here there is also a saturation block that allows the closure of the valve when the level of the fluid in the tank is zero.
The two body side forward tanks are connected to the Body Center Forward Tank. This is schematically the same as the center aft tank and is connected directly to the engine. The two flow rates coming out of these two subsystems must therefore support the flow rate required by the motor. For this reason a hydraulic flow rate sensor measures flow rates and is located between tanks and engine.
The following figure shows the complete model of the propellant subsystem. The yellow lines represent the physical connections between the various parts of the system. The red lines instead allow you to connect the blocks to the scopes. There are in fact some scopes scattered around the scheme. Two of these in particular, namely the Volume Tanks and FuelFlow scopes, allow you to view respectively the trends of the fluid level of each tank and the flow rates from the central aft tank and forward tank.
The next chapter will report on the trends and results obtained.

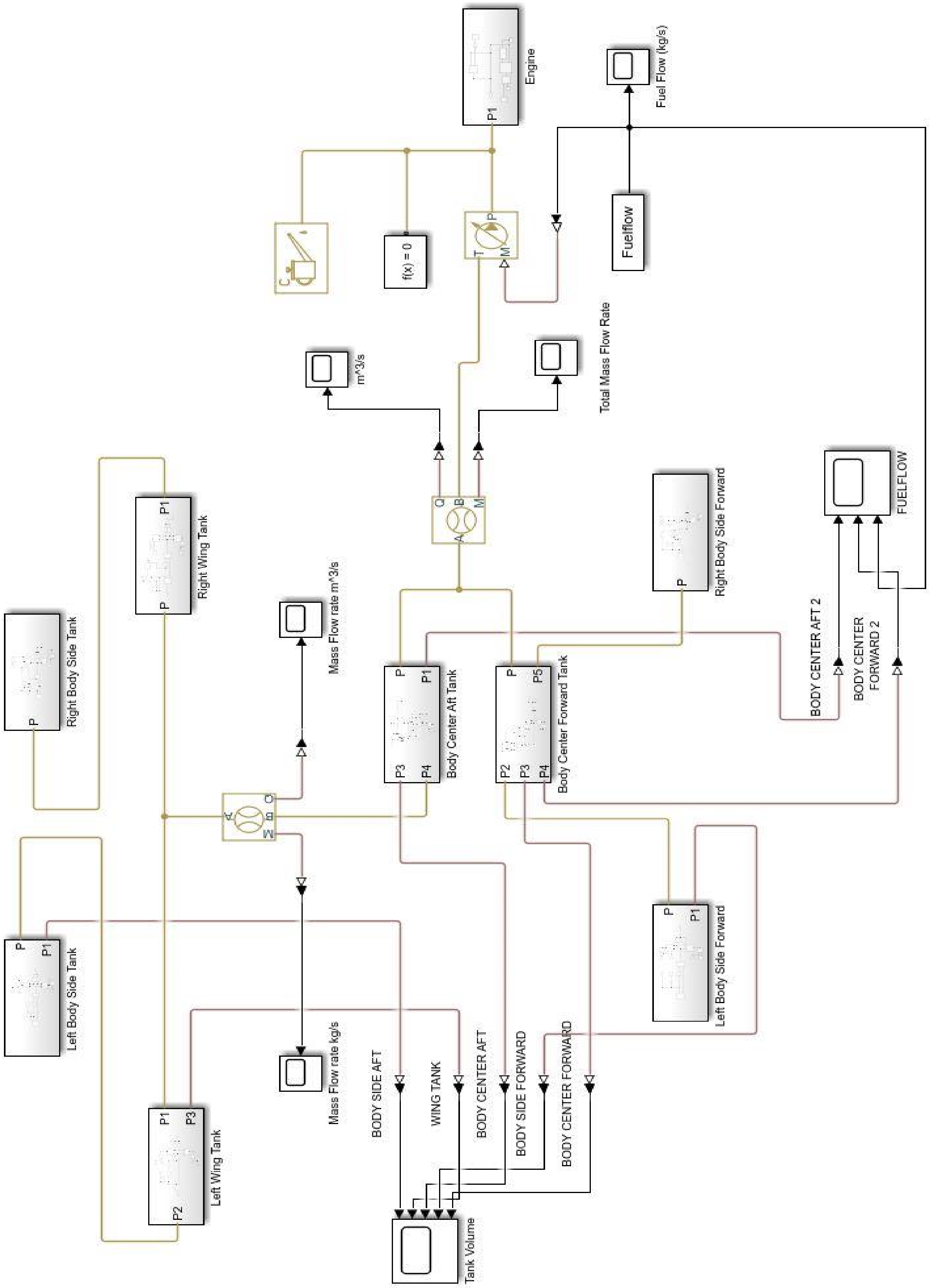

Figure 5.12 Propellant System Model

6 RESULTS AND COMMENTS

This chapter considers and discusses the results of a case study that was performed on the reference hypersonic aircraft. In particular, the trends of the variations of the volume of fuel inside the tanks as a function of the mission time of 7000 seconds are reported, based on the architecture described in the previous chapter, using the Simscape model made in the Matlab-Simulink environment.
The graphs were obtained in a iterative way by varying the input parameters such as the values of the valve passage areas, the size of the valve openings, as well as the fluid speeds and the inlet and outlet flow rates of the primary tanks. Of fundamental importance were the values of the signals entering the directional valves placed before the central tanks, that regulate the flows from auxiliary tanks.

The most likely flow profile created, even if approximated through straight lines, is shown in Figure 5.1, even if approximated through straight lines. The curve in the first phase of the mission has a constant course, and then decreases to 700 seconds. The peak is reached at 1000 seconds, when the capacity required by the engines is equal to 100 kg/s. From 2000 to 7000 seconds the curve decreases slightly from 22 kg/s to 16 kg/s. The required capacity is not cancelled because the mission has not yet been completed.

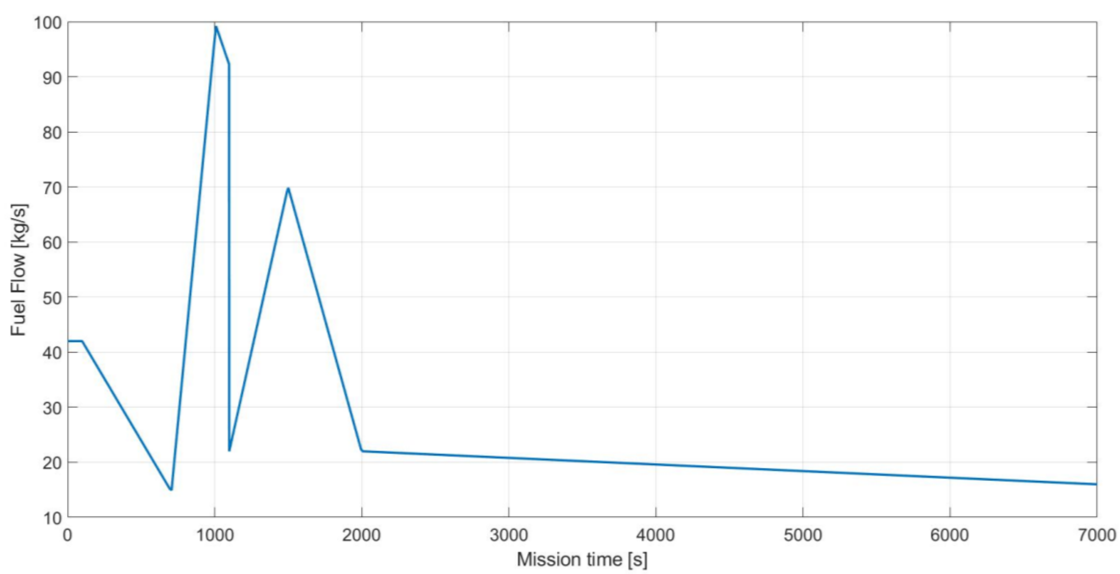

Figure 6.1 Fuel Flow profile

Figure 5.2 shows the trends of the capacities in kg/s of the primary tanks Body Center Aft and Body Center Forward as a function of the mission time. The red curve is the flow rate required by the engine.

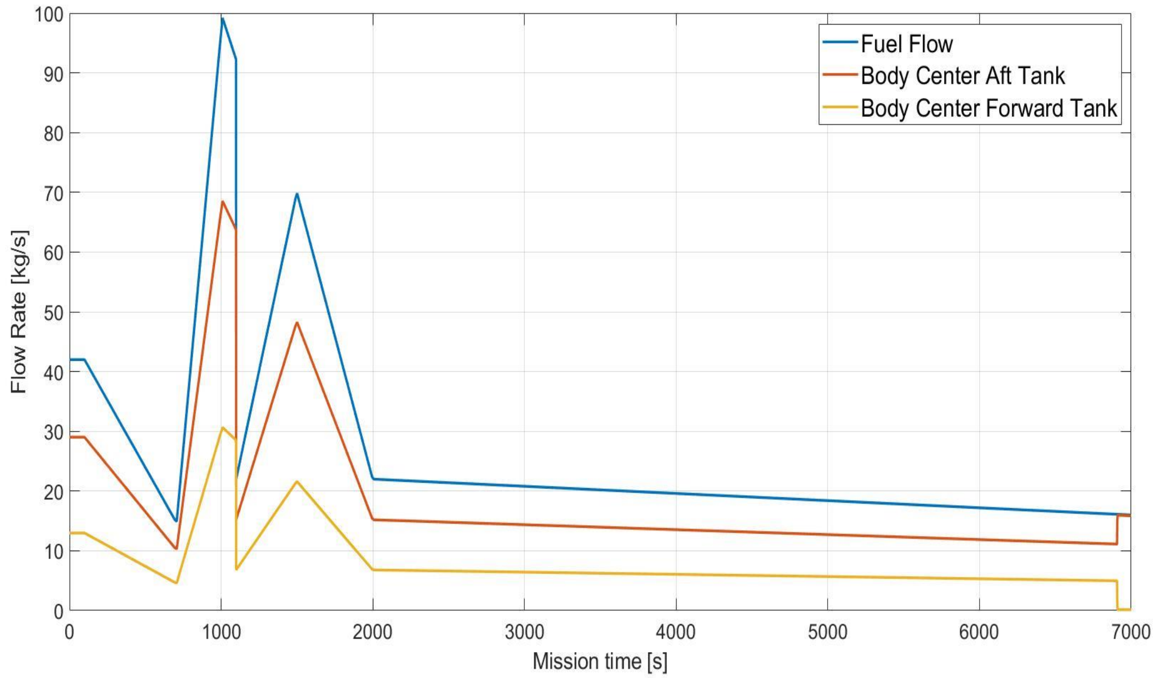

Figure 6.2 Fuel Flow Rates trends vs Mission Time

The flow rates are in line with those required and follow the trend fairly well, even if they remain slightly lower. In some sections the curves overlap. Even when at 1000 seconds the flow rate required by the motor reaches the peak value of 100 kg/s, the primary tanks are able to meet the demand. It can be deduced therefore that for the entire duration of the mission the required values seem to have been satisfied and are in line with the imposed requirements.

At this point, the trends of the changes that accur in the volume of liquid in the tanks are shown.

In particular, the trends of the Body Central Forward Tank and of the Body Side Forward Tanks is shown below.

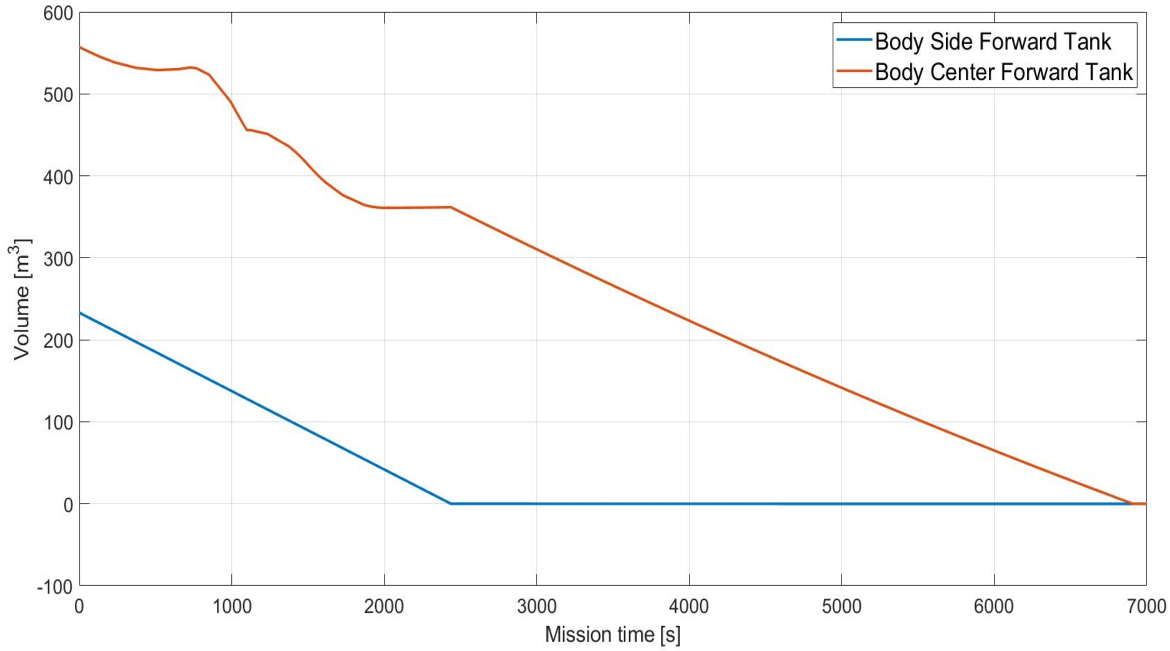

Figure 6.3 Tanks Volume vs Mission Time

The yellow curve represents the side forward tanks. The initial value of the volume is 233 m^3. This value decreases linearly, reaching a zero value at a time of about 1500 s and remains constant for the rest of the mission. At this point, the saturation block is activated and the directional valve closes. This means that the fuel contained in the side tanks is only used during the subsonic cruise phase. The tanks behave like real secondary tanks, in fact, as mentioned above, they are the first ones to empty.
The blue curve represents the volume variation as a function of the time of the forward primary tank. It has the typical trend of the primary tanks, which as is known are the last ones to empty. In reality, the zero value is not reached in this case, but this is due to the fact that the mission time is less than the actual duration of 10500 seconds. When the side tanks are completely emptied, the curve begins to decrease linearly. In the early stages of the mission, the curve does not have a constant trend, but one could say that it decreases following what is the request for flow rate. All this can be seen in the following figure, which shows the trend of the main tank only.

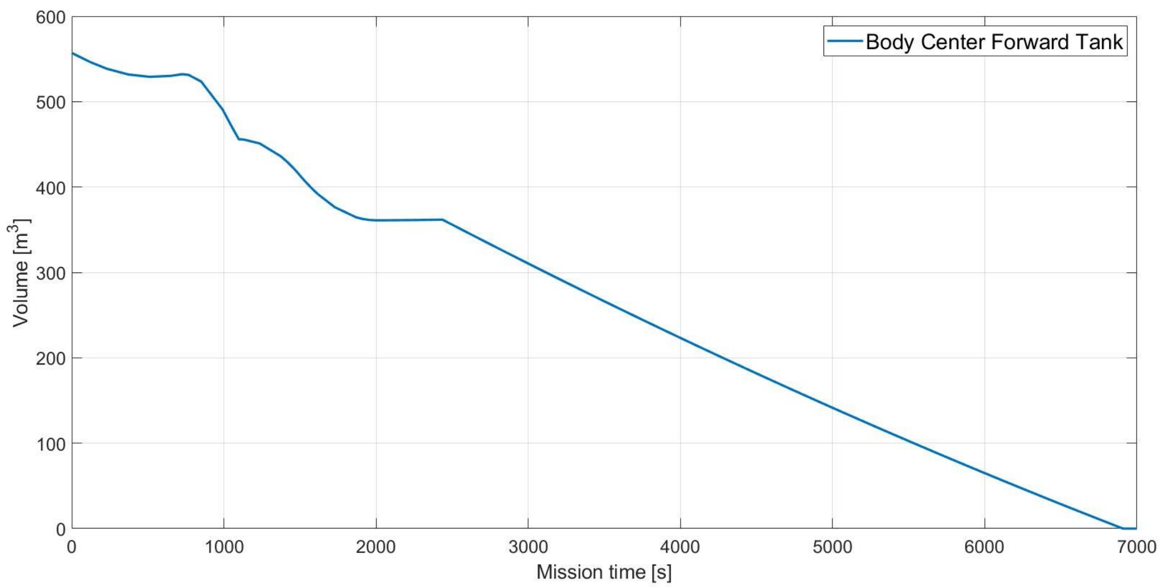

Figure 6.4 Body Center Forward Volume vs Mission Time

Hence, the emptying of the main tank (Body Center Forward) seems quite likely.
This graph can be considered a valid example for the activity carried out. It reflects what was expected and can be used to derive a law for the emptying the tank. The same can be said for forward secondary tanks.
By achieving such a trend for all tanks, it is possible to understand how fuel consumption during the phases of the mission can influence the movements of the center of gravity of the entire aircraft. The results obtained can then be used to our advantage to control the position of the CoG.
The trends of the remaining tanks are notincluded in this report, as the results obtained are not reliable. In particular, the central aft tank shows an opposite trend to that which was expected. In future it will thus become necessary to proceed iteratively until results for all tanks converge.
In this analysis, the use of the Simscape library has been quite adequate, although considerable difficulties were encountered during the design phase, due to the peculiarities of the system and the fluid used.

7 CONCLUSIONS

The work presented is part of a broader work that embraces multiple domains of aerospace engineering.

One of the objectives of this paper was to analyse the advantages and disadvantages of using liquid hydrogen as a fuel in new hypersonic concepts. The analysis was carried out by exploring the key aspects that have emerged over the years through in depth research, that has led experts and engineers to confirm the feasibility of liquid hydrogen as an energy vector of the future. This research has highlighted the importance and impact of this use for hydrogen on aircraft design and performance, on associated necessary infrastructures, on safety, on handling and on costs.
Based on the reported evaluations, what can be deduced is that at the moment new challenges and possibilities must be pursued to make hydrogen the most publicized, environmentally benign alternative fuel, but that this is the right course to take.
Eventually, a trade-off analysis could be conducted to evaluate appropriate advantages and disadvantages of the use of various fuels, through the appropriate figure of merits, with the aim of determining which fuel could be the best one, in terms of its costs-effectiveness, safety, environmental compatibility, development of infrastructure for production, storage, transport codes and regulations.

This thesis also focused on an initial sizing of the cryogenic on board tanks of a hypersonic aircraft. The analysis has been carried out, giving particular attention to tank wall and insulation materials, geometrical, thermal and mechanical requirements. The results obtained are promising. Although within the limits set by the nature of the approach used, this constitutes a starting point for successive design phases and for future developments and achievements. The tank weight has a considerable share of the fuel weight and the insulation system is influenced by numerous factors, such as the mission profile.
It is interesting to compare the results obtained using the simplified approach with the reference values of the LAPCAT MR2.4 project.
The following table allows the comparison of the thicknesses of the insulation layer of the tanks.

	STRATOFLY VEHICLE	**LAPCAT MR2.4**
Body Center Aft Tank Thickness [m]	**0.0926**	**0.0981**
Body Center Forward Tank thickness [m]	**0.0762**	**0.0981**

Body Side Aft Tank Thickness [m]	**0.0157**	**0.0215**
Body Side Forward Thickness [m]	**0.0161**	**0.0215**
Wing Tank Thickness [m]	**0.0161**	**0.0430**

Table 19 Comparisons Between the Two Aicraft Configurations

It is also possible to compare the values of the entire thermal protection system:

	STRATOFLY VEHICLE	LAPCAT MR2.4
Insulation Weight [kg]	**7929**	**10301**
Stand Offs Weight [kg]	**9062**	**4575**
Covers [kg]	**33827**	**17076**
Total TPS [kg]	**50818**	**31952**

Table 20 Comparison Of TPS Weight

	STRATOFLY VEHICLE	LAPCAT MR2.4
Boil off Weight [kg]	**6157**	**7358**

Table 21 Comparison of Boil Off Weight

As it can be seen in these tables, values obtained from all this analysis are coherent in most cases, except for the covers weight. This term determines the importante difference between two weights of the Thermal Protection Systems of the two aircraft configurations.
By optimising the calculation process, the weights and dimensions of the aircraft's tank system can even be further reduced. In fact, after the preliminary sizing, a mass budget could be developed that redefines the distribution of masses among the various subsystems with greater precision. There are many design aspects that were not discussed in the paper, but which would certainly need to be explored in the future. Although the integration of hydrogen tanks into common aircraft appears to be challenging, future aircraft would be designed to accommodate new storage technologies.

The other significant aspect of this investigation, is the analysis of the propellant subsystem of the STRATOFLY vehicle, which considers the baseline configuration of LAPCAT MR2.4. The subsystem analysis was based on the model created in Matlab-Simulink Environment.

The aim was to evaluate the trends of the variations in the level of fuel (liquid hydrogen) in the tanks in order to obtain an emptying law, for a preliminary assessment of the repositioning of the centre of gravity. In the course of the study several reasonable approximations and compromises were included to achieve the objective and converge to satisfactory results. The iterative approach used has been helpful and essential in identifying the key points of the physical architecture model and the correct values for the input parameters and signals. The trends obtained for forward tanks are plausible and consistent, unlike primary aft tanks and their auxiliary tanks. Changing the tank hierarchy may result in different outcomes. This certainly leads to wanting to improve and optimize the model created. It turns out to be a valid proof for the work that has been done and can be an example for future architectures and configurations.

The whole analysis has been demanding because of the high level of innovation and complexity of a hypersonic transport vehicle and its design phases. Clearly, in the near future the project will gradually improve its systems and sub-systems, therefore, if a similar study is accomplished during a more advanced stage of the design of the hypersonic vehicle, the results will be more accurate.
Finally, the reader's attention is drawn to the fact that, with the technological progress made possible by the increasingly advanced tools for aircraft design and optimization and their subsystems, it is expected that in the next few years there will be a significant improving the performance. These developments will enable the spread of civil hypersonic transportation vehicles and future reusable launchers.

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