Integration and Design of Cryogenic Hydrogen Fuel Systems for Sustainable Commercial Aviation

Tea-Maria DIACONU*

*Corresponding author
Colegiul National “Emanuil Gojdu”,
Strada Spiru Haret 3-5, Oradea 410066, Romania,
tea.diaconu@gmail.com

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Abstract: *The transition to hydrogen-powered aircraft offers an opportunity to significantly reduce carbon emissions in commercial aviation. The use of renewable hydrogen in commercial aviation has the potential to significantly reduce the carbon footprint of the industry. Aviation currently accounts for around 3% of global carbon emissions, a figure that is projected to grow without the adoption of sustainable fuels like hydrogen [1]. Hydrogen can be stored as a compressed gas at high pressure and as a liquid at cryogenic temperatures. However, the unique properties of hydrogen, particularly its low density and cryogenic storage requirements need a complete redesign of aircraft fuel systems. The low density of hydrogen necessitates larger storage volumes compared to conventional fuels, and cryogenic storage requires maintaining extremely low temperatures to prevent boil-off, which can lead to significant fuel loss [2]. This research aims to develop innovative fuel system designs that can efficiently store and deliver cryogenic liquid hydrogen.*

Numerous tank designs including cylindrical, spherical, and double-walled configurations will be explored. Cylindrical tanks are commonly used for high-pressure gas storage and must be designed to withstand pressure loads effectively. Spherical tanks offer a lower surface area-to-volume ratio, which is advantageous for reducing heat transfer and boil-off. Double-walled configurations provide additional insulation and structural integrity, essential for maintaining cryogenic temperatures [3]. Additionally, effective heat management is crucial in hydrogen fuel systems. The research will explore strategies to recover waste heat from fuel cells or combustion processes, which can be utilized to improve overall system efficiency. This is particularly important in preventing excessive boil-off in cryogenic tanks, which can lead to increased pressure and potential safety issues. By conceiving aircraft designs optimized for either direct liquid hydrogen combustion or fuel cell propulsion, this research aims to create sustainable aviation solutions.

Furthermore, this study will develop a detailed thermodynamic model to simulate the behaviour of cryogenic hydrogen fuel systems under various operating conditions, including heat transfer, phase changes and boil-off effects. The goal is to optimize the design and operation of hydrogen fuel systems to achieve maximum efficiency and safety. The findings from this research aim to provide a comprehensive framework for the future of hydrogen-powered commercial aviation. By addressing the unique challenges of hydrogen storage and fuel system design, the study seeks to contribute to the development of sustainable aviation solutions that can significantly reduce the carbon footprint of the airline industry.

Key Words: *hydrogen aircraft, cryogenic fuel systems, tank design, safety, thermodynamic modelling, heat management strategies*

1. INTRODUCTION

The aviation industry is at a crucial juncture in its efforts to become more sustainable, facing increasing pressure over its role in global carbon emissions, which currently account for around 3% of the global total. As the demand for air transport continues to grow, the need for new solutions to reduce environmental impacts has become more urgent. Fossil fuels, currently the main global source of energy, are expected to become depleted in the future, so there is a need to reduce dependence on fossil fuels and develop new energy sources. There are many fuels that can replace fossil fuels [11], [12], [13], such as biofuels, natural gas and synthetic fuels, but these types of fuels generate CO_2 during combustion, because they are also composed of carbon. Ammonia is a fuel that does not produce CO_2 [9], [10], but is highly toxic, and at the same time it has a pungent odour. Hydrogen is another fuel that does not generate CO_2, and unlike ammonia, it is an odourless, tasteless and colourless gas. Therefore, one of the most promising alternatives is the use of hydrogen as a fuel source, which has the potential to greatly lower carbon emissions, especially when produced from renewable sources [5]. Switching to hydrogen-powered aircraft is not just a technological change; it requires a complete rethink of how aircraft are designed and how fuel systems work. Hydrogen can be stored either as a compressed gas or as a liquid at very low temperatures, which means that existing aviation fuel systems need a total redesign. Because hydrogen is much less dense than traditional jet fuels, it requires larger storage tanks. Additionally, storing it as a liquid means keeping it at extremely low temperatures to prevent it from evaporating and to ensure safety. These challenges call for creative design solutions that can effectively handle the storage and delivery of liquid hydrogen in a way that is both efficient and safe.

With a specific energy of 120 MJ/kg, hydrogen provides nearly/ almost three times more energy per kilogram than conventional fossil fuels, which typically provide around 43.2 MJ/kg. This significant energy advantage has led to its use in various applications, including space exploration. For instance, in 1966, hydrogen and oxygen were utilized as propellants in the second stage of the Saturn IB rocket, known as the S-IVB. Today, the development of launch vehicles that use hydrogen continues, highlighting its potential in high-energy applications. In aviation, the push for zero-carbon-emission aircraft has sparked interest in hydrogen as a viable fuel source. Major companies like Airbus are actively working on developing hydrogen-powered commercial aircraft, with a goal to bring them to market by 2035. Airbus has proposed several innovative aircraft concepts that utilize hydrogen, showcasing the industry's commitment to transitioning towards more sustainable aviation solutions [6].

When it comes to storing hydrogen, the method chosen largely depends on the specific needs of the application. There are two primary ways to store hydrogen: compressing it into a gas at high pressure or cooling it down to turn it into a liquid at cryogenic temperatures. Each method has its own advantages and drawbacks. One of the main benefits of storing hydrogen gas at high pressure is that it allows for storage at room temperature, which is more convenient for many applications. Typically, hydrogen gas is stored at pressures of either 35 MPa (350 bar) [14] or 70 MPa (700 bar) [15]. When hydrogen is compressed to these high pressures, its density increases significantly-from just 0.0852 kg/m^3 at room temperature and normal pressure to about 23.995 kg/m^3 at 35 MPa and 40.172 kg/m^3 at 70 MPa. This increase in density means that more hydrogen can be stored in a given volume, making it a practical choice for various uses, including in fuel cell vehicles. However, high-pressure hydrogen tanks come with their own set of challenges. To safely contain hydrogen at such high pressures, the tanks must be designed with strong materials and structures that can withstand the intense forces involved. This often results in heavier tanks, which can add to the overall weight of the vehicle or system using the hydrogen. On the other hand, hydrogen can be stored as a cryogenic liquid. This method, as I specified before, involves cooling hydrogen to extremely low temperatures, which allows it to be stored in a much denser form. Liquid hydrogen takes up less space than gaseous hydrogen, making it a more efficient option for transporting large quantities. However, this method requires specialized equipment to maintain the low temperatures necessary to keep hydrogen in its liquid state, and it can lead to challenges such as boil-off, where some of the liquid hydrogen evaporates into gas.

Designing a cryogenic liquid hydrogen fuel tank is complex and involves several important factors to ensure safety and efficiency. Unlike gaseous hydrogen tanks, where the design pressure is straightforward, liquid hydrogen tanks must consider the tank shape, insulation performance, the amount of liquid hydrogen filled, and the fuel consumption rate. The tank's shape affects its structure and insulation needs, while effective insulation is crucial to minimize vaporization, which increases internal pressure. Additionally, a higher fill level leads to greater pressure build-up, and the rate of hydrogen consumption influences pressure behaviour over time. To create a safe and reliable tank, models that predict the maximum internal pressure based on heat transfer, fill level, and fuel usage must be developed. These models help optimize the tank's design to minimize pressure risks while meeting operational needs. In summary, careful consideration of these factors is essential for the effective use of liquid hydrogen as a sustainable aviation fuel. This research paper examines the integration and design of cryogenic hydrogen fuel systems for sustainable aviation, focusing on the unique challenges and opportunities associated with this change.

2. HYDROGEN AND ITS PROPERTIES

When burned, hydrogen produces only water vapour as a by-product, eliminating carbon dioxide (CO2) emissions entirely. In contrast, kerosene combustion releases CO2, nitrogen oxides (NOx), and particulate matter, contributing to air pollution and climate change. Hydrogen combustion can reduce the climate impact of aviation by up to 75%, while fuel-cell propulsion could achieve reductions of up to 90%. This makes hydrogen a cleaner alternative compared to conventional aviation fuels [16].

However, hydrogen must be stored at extremely low temperatures (around -253°C) to remain in liquid form, posing significant challenges for tank design and aircraft infrastructure compared to kerosene, which can be stored at ambient temperatures.

One of the standout features of liquid hydrogen is its low density, approximately 70.8 kg/m^3, which is significantly lighter than kerosene's density of 775 to 840 kg/m^3.

This lower density facilitates more efficient storage and transportation of energy per unit volume. Moreover, liquid hydrogen boasts an impressive energy content of about 122.8 MJ/kg, making it roughly 2.87 times more energy-dense than kerosene, which has an energy content of only 42.8 MJ/kg.

This high energy density can lead to reduced fuel weight, enhancing aircraft performance and range. In terms of thermal properties, liquid hydrogen has a specific heat of approximately 9.6 kJ/(kg·K), which is much higher than kerosene's 2.1 kJ /(kg·K).

This characteristic allows hydrogen to absorb more heat before its temperature increases significantly, making it advantageous for thermal management systems. Additionally, the latent heat of vaporization for liquid hydrogen is about 446 kJ/kg, indicating that while it requires more energy to vaporize compared to kerosene, this also allows for efficient energy storage capabilities [8].

Table 1. Comparative table of properties of hydrogen versus kerosene [7]

Property	Cryogenic Hydrogen	Kerosene
Density (kg/m^3)	71	780
Specific Heat (kJ/kg*K)	9.6	2.1
Latent Heat of Vaporization (kJ/kg)	446	250
Liquefaction Temperature (°C)	-253	15
Vaporisation Temperature (°C)	-253	150-300
Crystallization Temperature (°C)	-259	Not applicable
Energy Density (MJ/kg)	122.8	42.8
Volumetric Energy Density (MJ/L)	8.5	32
CO_2 Emissions (kg/kg fuel)	0	3.15

3. LATEST PROJECTS AND DEVELOPMENTS IN THIS FIELD

3.1 Chalmers University

Researchers at Chalmers University of Technology in Sweden are making significant advancements in hydrogen-powered aviation, aiming for nearly all intra-Nordic flight routes to be serviced by hydrogen aircraft by 2045. A recent study led by doctoral student Christian Svensson indicates that hydrogen flights could cover 97% of these routes and accommodate 58% of projected passenger volumes in the region. The research focuses on the adaptation of currently existing aircraft models to use hydrogen as a fuel vector by demonstrating pioneering technologies necessary for such a transition. Among the main developments, there is a new heat exchanger currently in the process of being patented, in collaboration with GKN Aerospace, which increases fuel efficiency by recovering the waste heat from a jet engine's exhaust and preheating super-cooled hydrogen fuel. This technology can mean fuel consumption decreases by about 8%, and aircraft range increases up to 10%, enabling the possibility of longer routes, such as Gothenburg to Berlin, estimated at about 450 miles. Apart from the heat exchanger, a lightweight fuel tank has been designed for the safe storage of liquid hydrogen in the type of aircraft where security is important, used for global efficiency optimization. According to Professor Tomas Grönstedt, leading the TechForH2 competence centre at Chalmers, if everything goes right, hydrogen flights could start flying commercial services as early as 2028. Thus, the emerging technology itself is in place, but there are many hurdles along the way, not the least of which concern the massive investments required in infrastructures and equally demanding partnerships in production, transport, and storage of green hydrogen. Assuming up to 30-40% of global aviation could be powered with hydrogen, it is estimated that upwards of close to 100 million tonnes of green hydrogen could be required annually by 2050 for the transition towards hydrogen aviation [17].

3.2 AIRBUS

In September 2020, Airbus unveiled three innovative aircraft concepts under its ZEROe initiative, all designed to operate on liquid hydrogen storage. The first two concepts are reminiscent of existing aircraft designs: one features turbofan engines capable of accommodating 120-200 passengers over a range of 2,000 nautical miles [4], while the other is equipped with turboprop engines for up to 100 passengers with a range of 1,000 nautical miles. Both models are engineered with rear-mounted hydrogen tanks that utilize vacuum insulation to maintain the extremely low temperatures required for liquid hydrogen storage, which is crucial for maximizing fuel efficiency and safety. The third concept is a blended-wing body design that optimizes internal hydrogen storage and matches the range of the turbofan model, showcasing Airbus's commitment to exploring diverse configurations for sustainable aviation.The ZEROe initiative aligns with the European Union's hydrogen strategy, highlighting aviation's potential to adopt sustainable fuel technologies from other sectors. This ambitious project not only aims to develop hydrogen-powered commercial aircraft but also emphasizes the importance of creating an ecosystem for hydrogen production and distribution at airports. By targeting a market introduction by 2035, Airbus is actively addressing the aviation industry's significant carbon footprint, which currently accounts for approximately 2.8% of global CO2 emissions. As part of this effort, Airbus is exploring both hydrogen combustion and fuel cell technologies, intending to leverage the benefits of each approach to achieve zero-emission flights [4].

Fig. 1 Aircraft models designed by Airbus under the ZEROe project [4]

4. TANK DESIGN

The design of cryogenic hydrogen storage tanks is extremely important for the successful integration of this fuel into aviation systems. When a fuel cell is in use, one of the biggest concerns is that cracks can form in the hydrogen tank, leading to leaks, especially in very cold conditions. These cracks can happen in composite materials, made of different substances, because the materials expand and contract at different rates when temperatures change. Cracks might also start due to physical stress during operation or thermal stress when filling the tank with hydrogen. If a crack causes a leak in an aircraft's hydrogen tank, it's important to ensure that the hydrogen escapes upward into the air. This way, if it catches fire, there are measures in place to keep the fire contained to a small area. To prevent cracks from spreading once they start, it's crucial to use materials that limit how far a crack can grow. Keeping cracks small helps reduce hydrogen leaks. This analysis explores three primary tank designs; cylindrical, spherical, and double-walled configurations, focusing on their applications in cryogenic hydrogen fuel systems for sustainable aviation and the design of a suitable tank for the next generation of hydrogen-powered aircrafts.

4.1 Cylindrical Fuel Tanks

I am going to start off by analysing the cylindrical shape first. The cylindrical shape allows for effective stress distribution under pressure, which is essential when storing LH_2 at approximately -253°C. This design minimizes the risk of structural failure due to thermal contraction and pressure fluctuations during operation.

However, while cylindrical tanks are efficient in terms of material usage, they require a larger volume compared to their energy content when storing LH_2. This is particularly challenging given that hydrogen's volumetric energy density is significantly lower than that of conventional jet fuels, necessitating careful consideration of tank size and placement within the aircraft structure. One of the main challenges with cylindrical tanks is managing heat transfer. The larger surface area relative to volume can lead to increased heat absorption, causing boil-off losses. Effective insulation techniques, such as vacuum insulation or multi-layer insulation (MLI) are necessary to minimize these losses and maintain LH_2 at cryogenic temperatures. In conclusion, cylindrical tanks are commonly used in smaller aircraft or drones where space constraints are less critical. Their design allows for easier integration into existing aircraft structures, making them a practical choice during the transitional phase towards hydrogen-powered aviation [18], [19], [20].

4.2 SPHERICAL TANKS

The spherical shape provides uniform stress distribution across the entire surface area, significantly enhancing structural integrity under high pressures. This characteristic is crucial for maintaining safety standards when storing LH_2, which can expand rapidly if not properly contained. Spherical tanks have a lower surface area-to-volume ratio compared to cylindrical tanks, which minimizes heat transfer and reduces boil-off rates. This efficiency is particularly beneficial in aviation applications where maintaining low temperatures is paramount for performance and safety.

Moreover, spherical tanks can be designed to fit more compactly within the fuselage of an aircraft, allowing for better utilization of space while maintaining balance and weight distribution. This configuration can help mitigate issues related to the aircraft's centre of gravity that arise from using larger cylindrical tanks. The absence of sharp angles in spherical designs reduces potential points for leaks or structural weaknesses. Additionally, their robust construction allows them to withstand extreme conditions associated with cryogenic storage.

In conclusion, spherical tanks are ideal for larger aircraft that require significant amounts of LH_2 for extended flights. Their design supports long-range operations while ensuring safety and efficiency in fuel management [21].

4.3 Double-Walled Tanks

To begin with, the double-walled construction provides an additional layer of security against leaks or ruptures. In the event of a failure in the inner tank, the outer wall serves as a secondary containment measure, preventing environmental contamination and ensuring compliance with stringent aviation regulations. Double-walled tanks typically incorporate advanced insulation materials between the two walls. This design minimizes heat influx and helps maintain the cryogenic temperatures necessary for LH_2 storage. Effective thermal management is crucial to prevent boil-off and maintain fuel efficiency during flight operations. These tanks often meet or exceed industry standards for hazardous material storage, making them suitable for use in commercial aviation where regulatory compliance is paramount. Their design facilitates easier inspection and maintenance due to their robust construction.

In conclusion, double-walled tanks are particularly useful in scenarios where safety is a primary concern, such as transporting LH_2 between ground facilities and aircraft or during refuelling operations. They can also be integrated into hybrid systems that combine hydrogen combustion with fuel cell technologies [22].

4.4 Comparative Analysis

The following table shows the key differences between cylindrical, spherical, and double-walled tank designs specifically for cryogenic hydrogen fuel systems.

Table 2. Differences between cylindrical, spherical, and double-walled tank designs specifically for cryogenic hydrogen fuel systems

Characteristics	Cylindrical Tank	Spherical Tank	Double-Walled Tank
Stress Distribution	Effective under pressure	Uniform across surface	Enhanced with secondary containment
Surface Area-to-Volume Ratio	Higher ratio, more heat absorption	Lower ratio, minimizes heat transfer	Similar to cylindrical
Heat Transfer Management	Needs advanced insulation	Efficient thermal management. Compact fit	Advanced insulation between walls
Space Utilization	Moderate; it requires a larger volume	Compact fit within fuselage	Flexible design for inspection
Safety Features	Basic; potential leak points at angles	Fewer leak points, robust construction	Secondary containment for leaks and ruptures
Ideal Applications	Smaller aircraft or drones	Larger aircraft for long-range flights	Transporting LH_2 and refuelling operations

4.5 Conclusions

Ultimately, the choice between cylindrical, spherical, or double-walled tank designs depends on factors such as aircraft size, LH_2 capacity requirements, space constraints, and safety considerations. Spherical tanks provide optimal efficiency and safety for larger aircraft (e.g. A380), while cylindrical configurations may be more suitable for smaller platforms (e.g. A321). Double-walled tanks excel in applications requiring maximum containment and insulation, such as transportation and refuelling (e.g. long-duration flights).

4.6 Optimal Tank Design

To avoid changing the airplane's outer shape, which could lead to a complete redesign of its structure, I decided to use a tank placed inside the fuselage and the other one place inside the wings. This tank will be a non-integral type, meaning it won't be part of the aircraft's structure. If an integral tank was used, the redesign the entire framework would’ve been necessary. Therefore, the tank will be designed to fit within the airplane's cross-section. For the optimal tank design, I opted for a cylindrical tank due to its numerous advantages in the context of storing liquid hydrogen (LH_2). The cylindrical shape provides effective stress distribution under pressure, which is crucial for safely containing LH_2 at temperatures around -253 °C. This design minimizes the risks of structural failure from thermal contraction and pressure fluctuations, making it particularly suitable for aviation applications. The shape allows for easier integration into existing structures during the transition to hydrogen-powered aviation, facilitating a smoother adaptation process. Considering that the liquid hydrogen is pushed against the wall at the back of the tank during take-off, the high pressure requires greater strength there. However, sizing a cryogenic tank involves four essential steps:

Selecting the Geometry: Determining the optimal shape of the tank to meet specific requirements.

Mechanical Design: Developing the mechanical design to calculate the necessary wall thickness to withstand internal pressures.

Thermal Design: Assessing heat transfer, including heat entering the tank and affecting the outer wall.

Boil-Off Consideration: Accounting for boil-off mass to prevent explosion risks, as some liquid hydrogen will inevitably boil off due to imperfect insulation. Effective insulation is crucial to minimize boil-off and maintain safety.

4.6.1 Fuel Tank Shape

The design for the fuel tank integration within the aircraft structure will utilize a cylindrical tank configuration, specifically tailored for the A321 model. This cylindrical shape is optimal for maximizing fuel storage capacity within the narrow fuselage while conforming to its contours, thereby minimizing modifications and reducing drag during flight.

4.7 Tank Materials

The materials used in the design of this optimized tank are:

For the inner wall: aluminium alloy 2219 T851 (1),

For insulation: Two layers of polyurethane foam with maximum density (2),

Vapour barrier: Sieve + extended filter mesh resembling very thin sponge pressed tightly together (3),

Exterior: Carbon fibre (4).

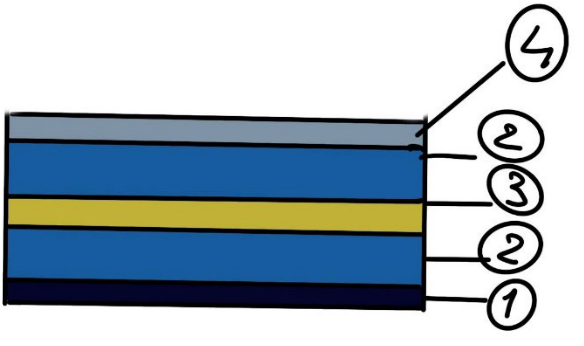

Fig. 2 Representative design for the layers found in the tank design

4.7.1 Insulation Choice

Polyurethane foam insulation has been chosen for its exceptional thermal resistance, which is vital for maintaining the low temperatures necessary for cryogenic fuel storage. This material offers high thermal resistance, ensuring that cryogenic fuels remain cold and stable, thereby enhancing safety and operational efficiency. The foam's ability to expand and fill gaps creates an airtight seal, effectively preventing air leaks that could lead to temperature fluctuations and compromise fuel integrity. Additionally, polyurethane foam is impermeable to water, protecting the fuel from moisture ingress. Its formulation also inhibits mould growth, further safeguarding the stored fuel from contamination.

Moreover, polyurethane foam is characterized by its durability; it has a long lifespan without sagging or degrading over time, which reduces the need for frequent maintenance and replacements. However, it is crucial to acknowledge potential safety concerns; burning polyurethane foam can release toxic fumes during emergencies. Therefore, careful material selection and adherence to safety protocols are imperative when employing this insulation type in applications involving cryogenic fuels [23].

4.7.2 Vapour Barrier

In addition to these steps, incorporating a vapour barrier is vital for preventing leaks of hydrogen or air from entering the tank. The vapour barrier ensures that no external air can infiltrate, which could compromise the integrity of the cryogenic environment and lead to safety hazards. It also helps contain the hydrogen within the tank, minimizing the risk of loss and ensuring efficient operation. I opted for a filter screen with an open structure, similar to a very thin sponge, as a vapour barrier.

The design will be of a molecular sieve that involves a dense material structure characterized by relatively large components that effectively prevent air from penetrating between the molecules. This arrangement is crucial for applications requiring high levels of insulation and separation, such as in cryogenic systems or gas purification processes. The filter operates similarly to a pressed sponge, consisting of numerous layers that create a complex network of pores. These pores are uniform in size, allowing the sieve to selectively discriminate between molecules based on their dimensions. At the macroscopic level, this layered structure can encompass hundreds of layers, each contributing to the overall performance by ensuring that larger molecules are unable to penetrate while smaller ones can pass freely.

4.7.3 Fairing

As for the fairing, the tank cannot be constructed from an ideal adiabatic shell. And for safety precautions, the exterior of the tank should be fireproof. However, there are 2 main options for fairing design: carbon fibre or fibreglass. When comparing fiberglass and carbon fibre for use in cryogenic hydrogen tanks, carbon fibre emerges as the superior choice due to several key factors. Carbon fibre boasts a higher strength-to-weight ratio, making it significantly lighter while providing greater structural integrity, which is essential for aviation applications where weight savings are critical. Additionally, carbon fibre exhibits better performance at extreme temperatures, effectively resisting micro cracking that can occur in fibreglass when exposed to cryogenic conditions. This resistance is crucial, as micro cracks can lead to leaks and compromise the tank's integrity. Furthermore, carbon fibre's durability and resistance to environmental degradation enhance its suitability for long-term use in harsh conditions. While fiberglass may be more cost-effective, the enhanced performance, lower weight, and superior thermal stability of carbon fibre make it the better option for cryogenic hydrogen storage applications [24].

4.8 Mechanical Design

4.8.1 Longitudinal Stress

Longitudinal stress (2) is a critical consideration in the mechanical design of liquid hydrogen (LH_2) tanks, primarily due to the unique properties and challenges associated with storing cryogenic fuels. When a liquid hydrogen tank experiences internal pressure, longitudinal stress is generated along its length (1), which is essential for ensuring the structural integrity of the tank. This internal pressure arises from the stored hydrogen and any thermal expansion or boil-off that may occur, necessitating careful analysis to prevent structural failure. The formula for calculating longitudinal stress (2) can be expressed as:

$$E\frac{\Delta l}{l_0} = \frac{F}{S} \tag{1}$$

$$\sigma = \frac{F}{S} \tag{2}$$

where E represents the elasticity constant, Δl denotes the relative elongation, l_0 is the initial length, σ signifies the longitudinal stress, S is the surface area, and F is the force considered to have elastic properties. This relationship highlights how internal forces acting on the tank contribute to elongation and stress, emphasizing the importance of material selection and design parameters in maintaining safety and performance under operational conditions.

4.8.2 Wall Thickness

The differing densities of liquid hydrogen (LH_2) and kerosene, as outlined in the table on slide 9, indicate that LH_2 is approximately ten times less dense than kerosene. Consequently, the required wall thickness for LH_2 tanks will be roughly nine times smaller than that of tanks designed for kerosene. For standard steel kerosene fuel tanks, the typical wall thickness is around 4 mm, although this can vary based on specific design and application requirements. To estimate the wall thickness for a liquid hydrogen tank, we can apply the ratio derived from their relative densities. Thus, the wall thickness for an LH_2 tank can be approximated using the formula, $T_{LH_2} = \frac{T_k}{9}$ resulting in an estimated thickness of approximately 0.44 mm, contingent upon the quantity of liquid hydrogen stored. The thickness of the alloy will also be determined by considering the pressure difference between ground level and cruising altitude (5). The atmospheric pressure at sea level (3) is given as:

$$P_0 = 10^5 \frac{N}{m^2} \tag{3}$$

Using the barometric formula, the pressure at a given altitude h (4) can be expressed as:

$$P(h) = P_0 e^{-\rho g h} \tag{4}$$

where $e \approx 2.71$ is the base of the natural logarithm.
For an altitude of 10,000 meters, this becomes: $P(10000) = 10^5 e^{-2700}$
The resulting pressure difference (5) is then calculated as:

$$\Delta P = P_0 - P(h) \tag{5}$$

4.8.3 Maximum Force Derived from Unit Stress

This alloy can withstand a very high force up to the breaking limit, resulting in normal operating conditions where hydrogen vapours cannot create such pressure. (The pressure at which the tank would be destroyed is hundreds of thousands of times greater than the maximum vapour pressure). The properties of this alloy include:
Density: Approximately 3.1 g/cm³
Modulus of Elasticity: Approximately 73 GPa [26]
Given these properties, we can derive the maximum force F (7) (6) that the alloy can withstand per unit surface area S using the relationship established by the modulus of elasticity:

$$E = \frac{F}{S} \tag{6}$$

From this, we can rearrange to find:

$$F = E \cdot S \tag{7}$$

This calculation indicates that under normal operating conditions, aluminium alloy 2219 T851 can sustain a maximum force of approximately 73 billion newtons when subjected to significant inertial forces during flight. This high level of strength ensures that the material remains stable and secure even in extreme conditions where inertial forces may be substantial.

4.8.4 Gravity Centre Configuration

In a cylindrical tank, the centre of gravity is typically located along the central vertical axis, which runs through the midpoint of the tank's height. For a uniform cylindrical tank, this point is situated at half the height of the cylinder. However, when filled with liquid hydrogen, the distribution of mass can shift due to the fluid's density and movement, particularly during manoeuvres or changes in orientation. As a result, the effective centre of gravity may be slightly lower than the geometric centre, reflecting the influence of the liquid's weight and its behaviour within the tank. The centre of gravity of each compartment with liquid hydrogen, during the movement of the airplane, must comply with the Pappus-Guldin theorem (8), which states that the area of the surface generated by a plane curve rotating around an axis in its plane (without intersection) is equal to the product of the curve's length and the circumference of the circle described by its centre of gravity. This can be mathematically represented as:

$$A = 2\pi x_G L \tag{8}$$

where x_G = the abscissa of the center of gravity of the curve.

4.9 Thermic Design

4.9.1 Material Conductivity

Materials with low thermal conductivity are essential for insulation systems. These materials help maintain the cryogenic temperatures required for LH_2 storage by limiting heat transfer from the external environment. Common insulation strategies include multilayer insulation (MLI which has been used in this design; 2 layers of Polyurethane foam) which are particularly effective in minimizing heat flow into the tank.

4.9.2 Adaptation of Fourier’s Law for the Thermal Conductivity of Tank Materials

Fourier's Law (9) provides a framework for understanding heat transfer through conduction in materials, which is essential for analyzing the thermal conductivity of materials used in the construction of the optimal liquid hydrogen tank used in this research paper. The law (9) is expressed as:

$$\Phi = \frac{dQ}{d\tau} = -\chi \frac{dt}{dx} \tag{9}$$

where Φ represents heat flux in watts (W), Q denotes heat in joules (J), τ is time, λ is the thermal conductivity of the material (W/ (m·°C)), S is the surface area through which heat exchange occurs (m²), and $\frac{\mathrm{dt}}{\mathrm{dx}}$ is the temperature gradient (°C/m).

Taking into consideration Fourier's law (9) and the relationship $C_v = m \cdot N_A \cdot c_v$ where m is the mass of a molecule, the expression for the thermal conductivity coefficient (10) can be obtained as follows:

$$\chi = \frac{1}{3}\rho\bar{v}\lambda c_v \tag{10}$$

where ρ is the gas density, m is the mass of a molecule, and c_v is the specific heat capacity. This formulation highlights how molecular properties and material characteristics influence thermal conductivity, which is crucial for ensuring efficient thermal management in the LH_2 tank design.

Table 3. The thermal conductivity of the materials used in the tank design

Materials Used	Thermal Conductivity λ (W/mK) at a temperature of t=20°C
Aluminium	236
Titanium	22
Polyurethane Foam	0,035-0,040
Carbon Fibre	24

4.9.3 Thermal Resistance

The wall resistance is determined for a pressure that is at least five times greater than the maximum vapour pressure in the compartment at an external temperature of 60°C. It is important to note that thermal resistance diminishes with increasing temperature; as temperature rises, atomic thermal agitation intensifies, causing the metal to approach its melting point and lose rigidity.

4.9.4 Radiation

The Stefan-Boltzmann law of radiation (11) can be expressed mathematically as:

$$W(T) = \sigma T^4 \tag{11}$$

where W represents the energy emitted per unit area, T denotes the absolute temperature, and σ is the Stefan-Boltzmann constant.
In the context of the optimal cryogenic hydrogen tank operating at approximately 20 K (-253°C), the radiative heat loss is considerably minimal due to the fourth power dependence on temperature. At such low temperatures, the amount of radiation emitted is significantly lower than that at room temperature (300 K), rendering it relatively insignificant when compared to other heat transfer mechanisms, such as conduction. Moreover, the materials commonly utilized in cryogenic tanks typically exhibit low emissivity, which further mitigates radiative losses. Although the application of Stefan-Boltzmann's law (11) is pertinent in understanding thermal radiation, its practical impact on heat management is minimal [25].

4.9.5 Boil-Off Mass

To determine the mass of vaporized hydrogen (12), we employ the following equation:

$$Q_p = m_H \cdot \lambda_H \tag{12}$$

where λ_H represents the latent heat of hydrogen, Q_p is the heat absorbed, m_H denotes the mass of the vapour.
The vaporization rate (13) can be expressed as:

$$R = \frac{m_{LH2V}}{\Delta t} \tag{13}$$

where m_{LH2V} is the mass of vaporized liquid hydrogen.

4.9.6 Heat Management Strategies

During flight, liquid hydrogen absorbs heat from the external environment, leading to evaporation. To mitigate rapid vaporization, I opted for the implementation of a cooling system consisting of coils surrounding the tank. The efficiency (14) of this cooling system can be quantified by the equation:

$$\varepsilon = \frac{Q_{ced}}{L} \tag{14}$$

where $Q_{ced} = mc\Delta t$ represents the heat released, c is the specific heat, and $L = \frac{P}{\Delta t}$ denotes the heat transfer rate with P being the power of the cooling system.

This cooling system efficiently minimizes the heat absorption from the surrounding environment, resulting in a reduced evaporation rate of liquid hydrogen. By keeping the tank at lower temperatures, it not only maintains the liquid state of hydrogen but also improves safety by lowering the likelihood of rapid vaporization, which could cause pressure build-up and pose potential hazards during flight.

4.10 Thermodynamic Model

4.10.1 Fluid Dynamics

Bernoulli's Principle in Cryogenic Hydrogen Flow

In fluid dynamics, Bernoulli's Principle (15) describes how the velocity of cryogenic hydrogen flowing through a horizontal pipe with a variable cross-section affects pressure. As the velocity changes, a net force acts on the hydrogen, resulting in pressure variations along the pipe, despite constant elevation. The pressure difference between two points depends on both any height differences and the velocity differences at those points. This principle is particularly significant for cryogenic hydrogen, where density variations at low temperatures can be substantial. However, Bernoulli's Principle (15) applies only to isentropic flows, where the effects of irreversible processes, such as turbulence, and non-adiabatic processes, like thermal radiation, are minimal. In cryogenic hydrogen systems, turbulence can disrupt flow stability, leading to energy losses and fluctuations in pressure and temperature. Understanding these dynamics is essential for optimizing cryogenic storage and refuelling systems to ensure efficient and safe operations.

$$\frac{\rho v^2}{2} + \rho g h + p = ct \tag{15}$$

Dynamics of compressible fluid- adapted for cryogenic hydrogen

Cryogenic hydrogen flow can be categorized into two primary regimes: laminar and turbulent. In laminar flow, hydrogen molecules travel in parallel paths with minimal interaction, resulting in stable flow characteristics. Conversely, turbulent flow, which occurs at higher velocities, is characterized by chaotic fluctuations and the formation of vortices. This turbulence enhances heat transfer due to vigorous mixing within the fluid, significantly impacting temperature and pressure distribution. When analyzing the dynamics of compressible fluids in cryogenic hydrogen applications, it is essential to consider both flow regimes and the density variations that arise at extremely low temperatures. Understanding these dynamics is crucial for optimizing systems involving cryogenic hydrogen, as they influence efficiency and safety in storage and refuelling processes [27].

4.10.2 Inside the Tank

Stationary heat transmission refers to the process of heat transfer between two points where the temperature gradient remains constant over time (16), (17), and (18). This condition is characterized by a stable temperature difference where T_1 represents the interior temperature and T_2 the exterior temperature.

Under these circumstances, heat flows continuously due to the thermal agitation of molecules crossing the boundary in both directions. Heat flux in the direction of x will be determined precisely by the difference between the average energies $E_m{}^1$ (16) and $E_m{}^2$ (17) carried by each of the n molecules that traverse the surface element in both directions (the number n of molecules is constant in both directions, with pressure being constant at each point). The energies $E_m{}^1$ and $E_m{}^2$ correspond, by convention, to the temperatures T' and T'' (19) at the points located on either side of the surface element ΔS at the distanceλ. This description is applicable to cryogenic hydrogen as well, as the principles governing heat transfer remain consistent regardless of the specific fluid involved.

$$Q_1 = \frac{1}{6} n\bar{v}\mathrm{E_m}{}^1 \tag{16}$$

$$Q_2 = \frac{1}{6} n\bar{v}\mathrm{E_m}{}^2 \tag{17}$$

$$J_q = \frac{1}{6} n\bar{v}\Delta E_m \tag{18}$$

and finally,

$$T' - T'' = -2\lambda \frac{dT}{dx} \tag{19}$$

$dT = when\ \Delta T$ is very small
$dx =$ the distance between the 2 points (T_1, T_2)
$\frac{dT}{dx}$= temperature difference per unit length
<u>On terrain:</u>
T'= in the tank interior (the temperature of liquid hydrogen LH_2), mostly constant
T''= the tank's exterior wall temperature (it can be variable, because it changes throughout the flight – during take-off, cruising altitude, during descend)
$\bar{v}$ = average speed of hydrogen vapors

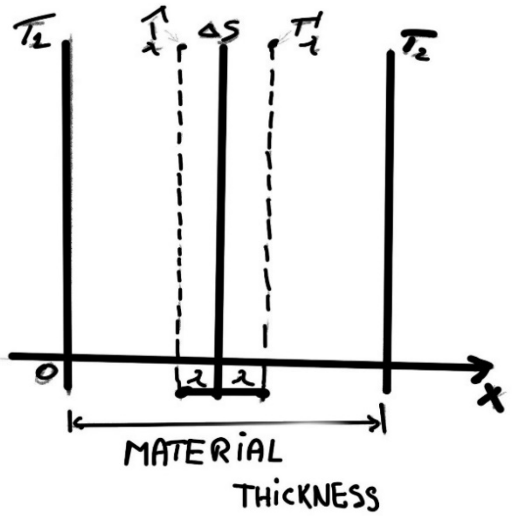

Fig. 3 Mathematical representation of heat transfer

Phase transformation:
The phase transformation occurs with heat exchange. Molecules transition from the liquid state to the vapour state due to heat absorption.
Heat received through pipes:
The heat entering through the pipes contributes approximately 1-2% to the heat received from the outside compared to that received by the surface of the tank. In the thermodynamic model of a cryogenic hydrogen tank, the most significant heat intake occurs for liquid hydrogen (LH_2).
The amount of heat lost through the structure
The amount of heat lost through the tank structure (20) can be quantified using the equation:

$$Q_m = m_r c_r \Delta T \tag{20}$$

where c_r can be calculated as:

$$c_r = \frac{m_{Al} \cdot c_{Al} + m_{Ti} \cdot c_{Ti}}{m_{Al} + m_{Ti}} \tag{21}$$

For this analysis, *I* considered an alloy mass of m_r=1 kg and a temperature difference of ΔT=1 K. This framework allows for an understanding of how heat loss impacts the efficiency and safety of cryogenic hydrogen storage systems, emphasizing the need for effective thermal management strategies.
The vapour pressure above the liquid hydrogen
The vapour pressure above liquid hydrogen (22) can be described using the equation of state:

$$P_V V_V = \frac{m_V}{\mu_{H_2}} RT \tag{22}$$

From this, we can express the vapour pressure (23) as:

$$P_V = \frac{RT}{\mu_{H_2}} \cdot \frac{m_V}{V_V} \tag{23}$$

Notably, since $\frac{RT}{\mu_{H_2}}$ is a constant, it follows that as liquid hydrogen begins to evaporate, the mass of the vapour (m_v) and its volume (V) will increase (24). Consequently, we can approximate:

$$\frac{m_V}{V_V} \approx \text{constant} \tag{24}$$

To maintain system stability and safety, it is advisable to keep the vapour pressure within the tank at approximately constant levels.

5. CONCLUSIONS

The transition to cryogenic hydrogen (LH_2) as a fuel source holds exciting promise for the future of aviation. With its remarkable energy density - about three times that of kerosene - LH_2 can power lighter, more efficient aircraft that can travel farther while producing only water vapour as a by-product. This means cleaner skies and a significant reduction in harmful emissions, aligning perfectly with our growing commitment to sustainability. However, the road to widespread LH_2 adoption isn't without its bumps. The current price tag of around €20 per kilogram is a tough sell compared to kerosene, which costs less than €3 per kilogram. This cost differential is a real challenge for airlines looking to make the switch. Additionally, we need to invest in new infrastructure to meet the unique requirements of liquid hydrogen, including advanced storage and transport systems that can keep it at extremely low temperatures. In essence, while LH_2 offers a bright path to greener aviation, we need to address these economic and logistical hurdles head-on. With continued innovation and investment, we can make liquid hydrogen a practical and sustainable fuel choice for the future of aviation. Together, we can make significant progress towards a cleaner, more efficient aviation industry that benefits both our planet and future generations.

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