



CRYOGENIC TANK SIZING MODEL FOR THE CONCEPTUAL DESIGN OF HYDROGEN-POWERED AIRCRAFT

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Abstract

Hydrogen-based propulsion is a promising avenue to reduce drastically aviation's CO₂ emissions from flight operations. However, due to the hydrogen's low volumetric density, this alternative fuel presents a challenge regarding storage volume and integration into the aircraft. Parametric models must be developed to allow the sizing and exploration of possible hydrogen storage tank layouts within the aircraft conceptual design while considering design requirements, such as safety considerations, and sufficient automation for integrating into an aircraft-level multidisciplinary design analysis and optimization (MDAO) framework. This paper presents one model and illustrates analysis capabilities, such as the variation of the tank's geometry and its impact on its volume and mass, which are essential for conceptual design. The model combines various methods from the literature into a new, completely parametric model that considers filling pressure, tank geometry, tank material, and installation constraints. The presented model allows the analysis of different tank configurations and layouts and trade-off studies on the gravimetric and volumetric efficiencies on the aircraft level. Four case studies illustrate the model capabilities for future business aircraft configurations. In summary, the presented tank sizing helps to establish a feasible design space for future, more environmentally friendly aircraft designs.

Keywords: Cryogenic Tank Sizing, Hydrogen-based Propulsion, Aircraft Conceptual Design, Multidisciplinary Design Analysis and Optimization

1. Introduction

The aviation industry is committed to reaching net zero carbon emissions by 2050 [1]. To ensure the competitive advantage of future aircraft regarding energy efficiency and environmental impact, the development of breakthrough technologies is essential. This entails the integration of advanced technology concepts and the adoption of more environmentally friendly energy sources [2]. Aviation stakeholders are pursuing the development of alternative propulsive technologies to reduce their carbon footprint. In this context, the Canadian collaborative research project "Exploration and modeling of alternative propulsion technologies for business jets" (EAP) addresses various alternative propulsion technologies for future business aircraft.

One of the initiatives toward alternative propulsion and research avenues for reducing fossil fuel burn is hydrogen-based propulsion. Hydrogen can be used either in direct propulsion, burned like a conventional fuel to power an engine, or in a fuel cell-based propulsion, used to produce electricity and power a motor. Compared with conventional fuel, hydrogen delivers three times more energy for the same mass, making it a promising alternative for propulsion usage. However, at ambient conditions, the volumetric energy density of hydrogen is nearly four times less than that of jet fuel; it needs to be compressed or liquified at cryogenic temperatures to be transported on board in sufficient quantities [3].

The challenge with hydrogen-based propulsion is the integration or storage of hydrogen in the aircraft, especially for smaller aircraft. Parametric models are required to allow the sizing and evaluation of the tanks to facilitate this process while also considering specific design requirements (i.e., safety and

operational requirements), particularly in the aircraft-level multidisciplinary design analysis and optimization (MDAO) context. On the one hand, placement safety constraints, such as rotor burst zones, need to be considered; on the other hand, the overall aircraft drag and weight should be minimized. In addition, operational constraints such as tank refilling and venting pressure, ground operation times, and outside temperatures impact the tank sizing and insulation requirements, all contributing to the mass and volume. Therefore, various tank sizes and placements require a highly flexible parametric tank sizing model.

The presented paper will review aspects to consider when sizing the hydrogen storage tanks and will present a sizing model elaborated around the volume and pressure of the hydrogen to be stored. The model evaluates the volume needed to store liquid hydrogen, given specific hydrogen properties and pressure requirements, the geometric constraints of the aircraft, and the tank structure. It allows a determination of the overall shape of the tank and, consequently, the space that needs to be allocated in the aircraft for it.

The paper outlines the methodology used to develop the tank sizing and weight estimation model and the applications of this model. Section 2 reviews key literature used in the development of this model. The methodology and the subcomponents of the tool are presented in section 3, and the possible applications of the tool and results are illustrated in section 4. Finally, section 5 provides some conclusions on the test cases conducted with the developed model.

2. Literature Review

The literature provides several studies and models on hydrogen storage technologies. Brewer [3] lays out the basics of integrating hydrogen technologies in aviation and presents a detailed review of the different components of the fuel containment system and design considerations. He discusses and compares the main types of tanks (integral and non-integral). The tank's volume is determined based on the amount of hydrogen it needs to carry, plus some allowance for the difference in tank dimensions at different temperatures. This textbook also lists the structural design criteria, i.e. the pressures and stresses the tank will be subjected to, the design criteria for insulation, and the comparison of several insulation concepts.

Building on [3], several researchers have studied or developed models for hydrogen tanks. Verstraete [4] developed a model for cylindrical hydrogen tanks and compared non-integral and integral tanks. The model considers the tank filling and venting pressure and the pressure fluctuations inside the tank. For the insulation of that tank, several insulation means were compared: foams, aerogels, vacuum, and multi-layer insulation (MLI). In [5], Verstraete et al. compare foam and MLI regarding the tank weight, the overall size, and the hold period. Following Verstraete's filling and venting pressure considerations, Winnefeld et al. [6] created a non-integral tank design model featuring ellipsoidal heads and elliptical shells, making the tank more versatile. This design model considers the geometrical, mechanical, and thermal aspects of the hydrogen tanks.

Building on the models developed by Verstraete and Winnefeld, other researchers have conducted studies on hydrogen storage. Palladino et al. [7] explore hybrid-electric propulsion architectures, including hydrogen fuel cells for regional aircraft. Parametric studies were conducted to explore the impact of these architectures on the performance of the aircraft. Mantzaroudis and Theotokoglou [8] use the Von Mises stress criterion to observe the structural behavior of the inner shell of the tank. They study the relationship between different tank geometrical parameters and the tank's mass.

The following works focused on different aspects of hydrogen tank design and its integration in an aircraft while adopting tanks with ellipsoidal heads. Colozza et al. [9] look at how the total mass of the tank is affected by the amount of insulation on the tank. Gomez and Smith [10] investigate the implementation of hydrogen fuel tanks in commercial airplanes according to two different layouts and perform a detailed structural analysis of the different tanks in these layouts. Similarly, Onorato et al. [11] study different tank layouts for commercial aircraft but focus on the pressure profile of the tank and the overall impact of the fuel system on the aircraft in terms of performance compared to a conventionally powered aircraft. Shank et al. [12] adopt a given geometry for cylindrical and spherical tanks at different conditions, namely on-ground and in-flight conditions, and compare different insulation materials applied to these different tanks. Sarkar et al. [13] study a cryogenic fuel system for

a narrow-body aircraft for a given mission profile for different insulation thicknesses and times of the day. Finally, Alsamri et al. [14] perform an analysis of the performance and emissions trade-offs for a business jet retrofitted with a hydrogen-powered fuel cell and discuss the sizing and placement of the hydrogen tanks.

In summary, the existing literature provides equations and applications for different tank geometries, materials, and insulation. The models developed in the literature take the filling level of the tank into account but lack details to calculate the different allowance percentages at venting pressure. Furthermore, the literature mainly presents studies made on cylindrical tanks and pre-defined tank configurations without addressing the safety considerations of the layout. The paper shows, therefore, the steps to a generalized approach for considering different boil-off percentage allowances and attempts to address tanks with more versatile elliptical shapes. Furthermore, in light of the need for safety considerations, the tool enables the exploration of different layouts and tank gravimetric efficiencies. The proposed tool aims to explore the integration of tanks of various shapes and placements within the aircraft.

3. Methodology

The objective of the model is to determine the size of the tank based on the amount of hydrogen that needs to be stored in it, hence ultimately allowing the exploration and definition of the tanks' layout and placement in the aircraft. The cryogenic tank sizing model is based on the energy required to complete a certain mission. Figure 1 summarizes the methodology, which is based on three steps: (1) calculation of the required hydrogen volume, (2) definition of the internal tank geometry (1st tank wall), and (3) definition of the external tank geometry (including the insulation and the wall material). Steps 2 and 3 can be iterative, depending on the installation constraints.

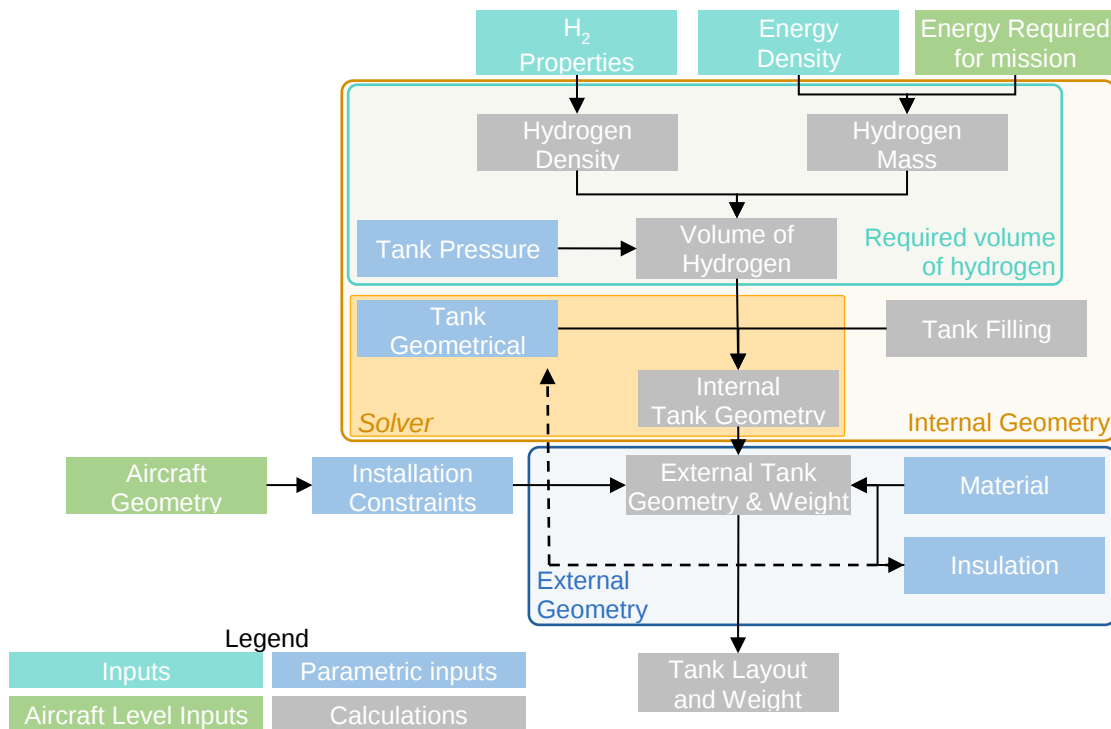


Figure 1 – Methodology overview for the hydrogen tank sizing

3.1 Calculation of the required hydrogen volume

A two-phase mixture is assumed to be stored; hence, the model uses parahydrogen thermodynamic properties for a liquid-vapor saturated state based on published engineering design data [15] and calculates the average hydrogen density in the tank. Figure 2 shows the density variation with pressure for different compositions of mixtures where the y parameter is the liquid volume fraction defined as the volume of liquid in the tank vs. the overall volume of hydrogen stored ($y = 0$ represents; therefore, fully gaseous hydrogen (g) and $y = 1$ is associated with liquid hydrogen (l)). Equation (1) was used to determine the density of the mixture for different fill levels.

$$\rho_{avg} = \frac{\rho_g \rho_l}{\left(\frac{\rho_g (1 - y)}{\rho_g (1 - y) + \rho_l y} \right) (\rho_l - \rho_g) + \rho_g} \quad (1)$$

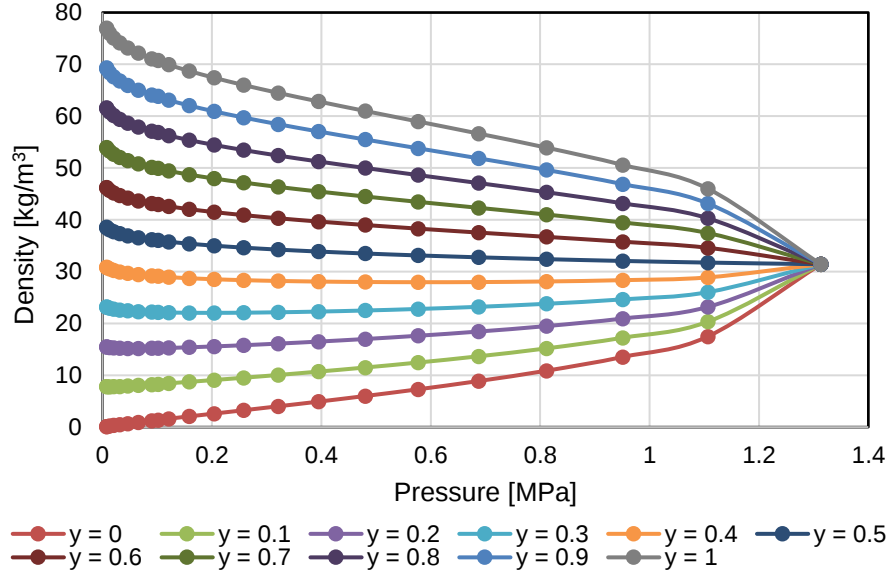


Figure 2 - Average density of hydrogen at various volume fractions

The two-phase mixture absorbs some of the heat that enters the tank, which leads to a rise in pressure. To minimize the risk of boil-off, the level up to which the tank is filled needs to be low enough to prevent excessive pressure rise [4]. In case of boil-off, a certain amount of gas needs to be available for venting. If a certain percentage of the total volume is desired as allowance at the maximum pressure of the tank (at venting pressure), the ratio of gas to the total volume at filling pressure needs to be determined. Therefore, the level at which the tank can be filled has to be defined so that there is a certain allowance at the maximum pressure. The fill level of the tank is determined based on Verstraete [4], and considers the design vent pressure and the filling pressure, as seen in Figure 3, where the fill level was determined using Equation (2). The fill level at filling pressure helps determine the tank volume needed to accommodate the amount of hydrogen to be stored.

$$y = \frac{\rho_g - \rho_{avg}}{\rho_g - \rho_l} \quad (2)$$

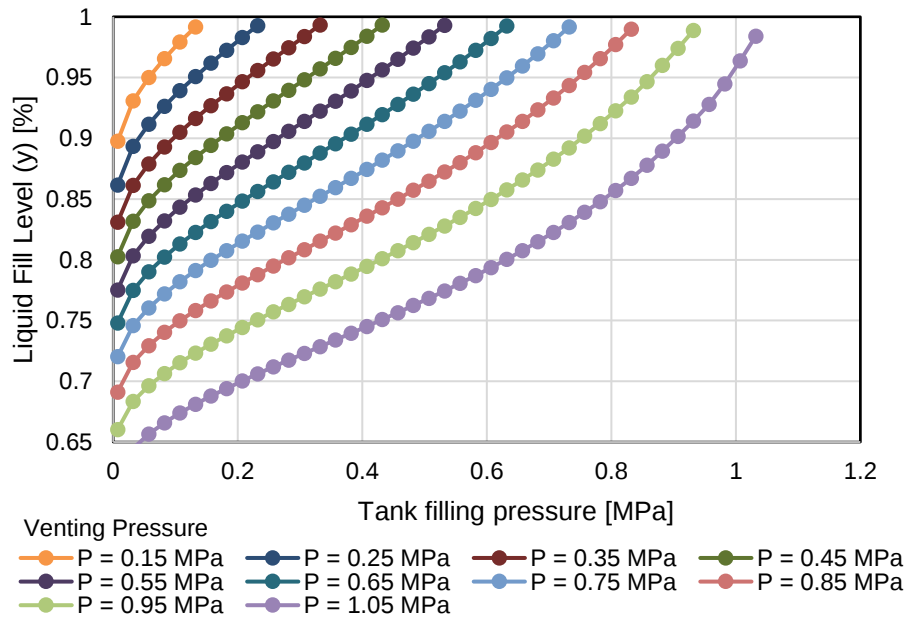


Figure 3 - Fill level with respect to various fill and venting pressures

3.2 Internal geometry of the tank

The tank's geometry is assumed to be composed of an elliptical cylinder shell and two ellipsoidal heads at each end, as described in Winnefeld [6] and shown in Figure 4. The parameter λ represents the ratio of the length of the shell vs. the total length of the tank, ϕ is the ratio describing the relationship between the ellipsoidal axes or how round the tank is, and ψ describes the shape of the tank heads or how protruded they are.

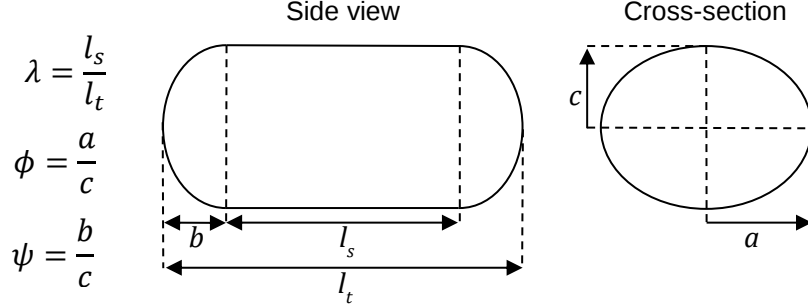


Figure 4 - Geometrical representation of a modeled tank (adapted from [6])

Having determined the tank's volume and defined three more parameters out of the eight presented in Figure 4, one can calculate the internal geometry of the tank. The solver shown in the methodology flowchart presented in Figure 1, solves for the unknown values in the following equations (3-8) describing the tank's geometry.

$$a = \left(\frac{3V_t\phi^2(1-\lambda)}{\pi\phi(2\lambda+4)} \right)^{1/3} \quad (3)$$

$$b = \psi c \quad (4)$$

$$c = \frac{a}{\phi} \quad (5)$$

$$l_s = \frac{V_t - \frac{4}{3}\pi abc}{\pi ac} \quad (6)$$

$$l_t = l_s + 2b \quad (7)$$

$$V_t = \pi a c l_s + \frac{4}{3}\pi abc \quad (8)$$

Section 4 describes some application cases in which the different parameter combinations are solved.

3.3 External geometry of the tank

After the tank's geometry is determined, the tank's surface area and mass can be established, considering the wall thickness needed to sustain the internal pressure and the material chosen for the tank. Since the hydrogen is maintained in a liquid state, the tank material and insulation chosen to maintain the hydrogen at cryogenic temperatures are an integral part of the modeling process and impact the external geometry and the overall weight of the tank. In addition, geometric constraints of the aircraft impact the layout of the tanks.

Three main insulation categories are typically cited for cryogenic purposes: foams, aerogels, and MLI (without or with a vacuum layer). The present study focuses on foams, aerogels and MLI without vacuum for simplification of the heat transfer calculations, and as it is the most prominent in the literature. Table 1 shows the characteristics of these main types of insulation.

Table 1: Insulation types characteristics (adapted from [16], [17])

Foams	Multi-layer Insulation	Aerogels
• Well established • Low density, lightweight • Relatively high thermal conductivity (14 – 33 mW/m·K)	• Well established • Low thermal conductivity (2 – 24 mW/m·K)	• Newer technology • Limited mechanical properties • Low thermal conductivity (0.6 to 12 mW/m·K)

The main parameters used for the comparison of the insulation materials are the thermal conductivity and the density of the material. A low thermal conductivity leads to a thinner insulation, while a low density leads to a low mass. An ideal material would, therefore, have low thermal conductivity and density. However, as seen in the benchmarked materials presented in Figure 5, none of the types of insulations have both advantages; a trade-off between the thickness (volume) and the mass of the different insulations is necessary. Figure 6 in section 3.4 illustrates the performance of the various insulation materials for different tank exposure times.

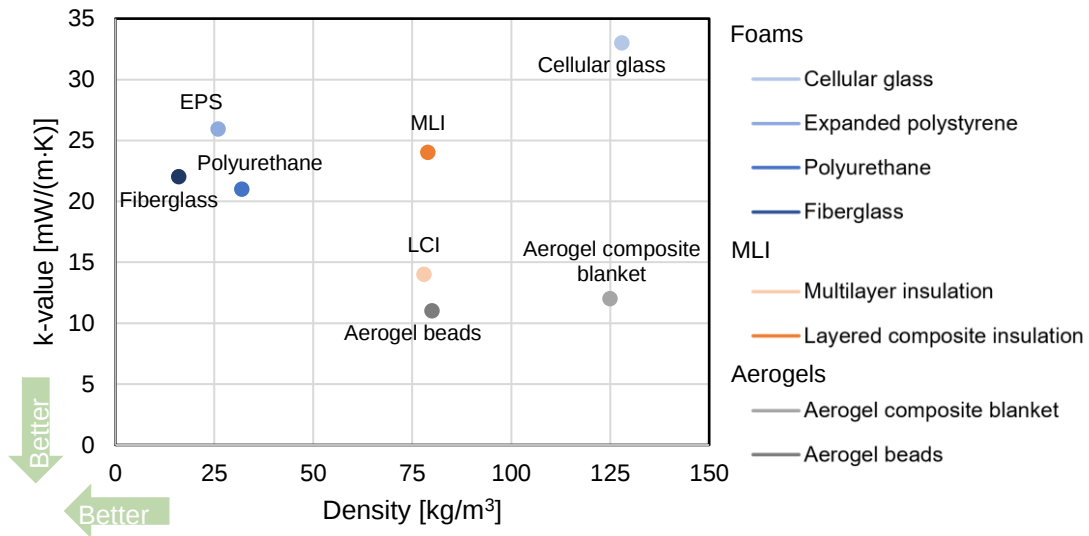


Figure 5 - Insulation materials properties

The foams tend to have a lower density (which is desirable) but a higher thermal conductivity (undesirable); on the contrary, the aerogels have a low thermal conductivity but a higher density. The MLI tends to be in the midrange of thermal conductivity and density. For MLI with a vacuum layer, the thermal conductivity can reach around 0.1 – 5 mW/m·K, leading to low heat transfer and requiring a double tank wall to maintain the vacuum [16], [17]. This insulation technology seems, therefore, very promising and will be integrated into a future version of the tool.

The heat from the environment entering the tank containing liquid hydrogen causes the liquid to boil. The gas resulting from the boil-off process has to be vented from the tank to preserve the tank pressure and is therefore lost to the environment. To minimize these losses, good insulation is necessary. To size the insulation of the tank, the thermal module of the tool takes into account the boil-off process and, therefore, the heat entering the tank. The inside and outside temperatures of the tank are key parameters in the insulation sizing. The thermal resistance and, therefore, the thickness of the tank are determined following heat transfer principles in one-dimensional conditions [18] and taking into account the geometry of the tank.

3.4 Summary and limitations

In summary, the hydrogen tank's internal sizing considers the amount of hydrogen to store and the associated volume required. The external geometry definition method allows the exploration of several insulation materials; it was cross-validated with test cases from the literature for in-flight and on-ground usage [12].

Figure 6 presents a study on different insulation materials for various exposure times of the hydrogen tank. The considered outside temperature is for hot-day on-ground conditions with a constant temperature over the considered period, leading to conservative results. The aim of the tool is to find

the most promising tank configuration as a first step. Future work will be to address the variation of temperature during the day by building a dynamic simulation leading to more detailed sizing.

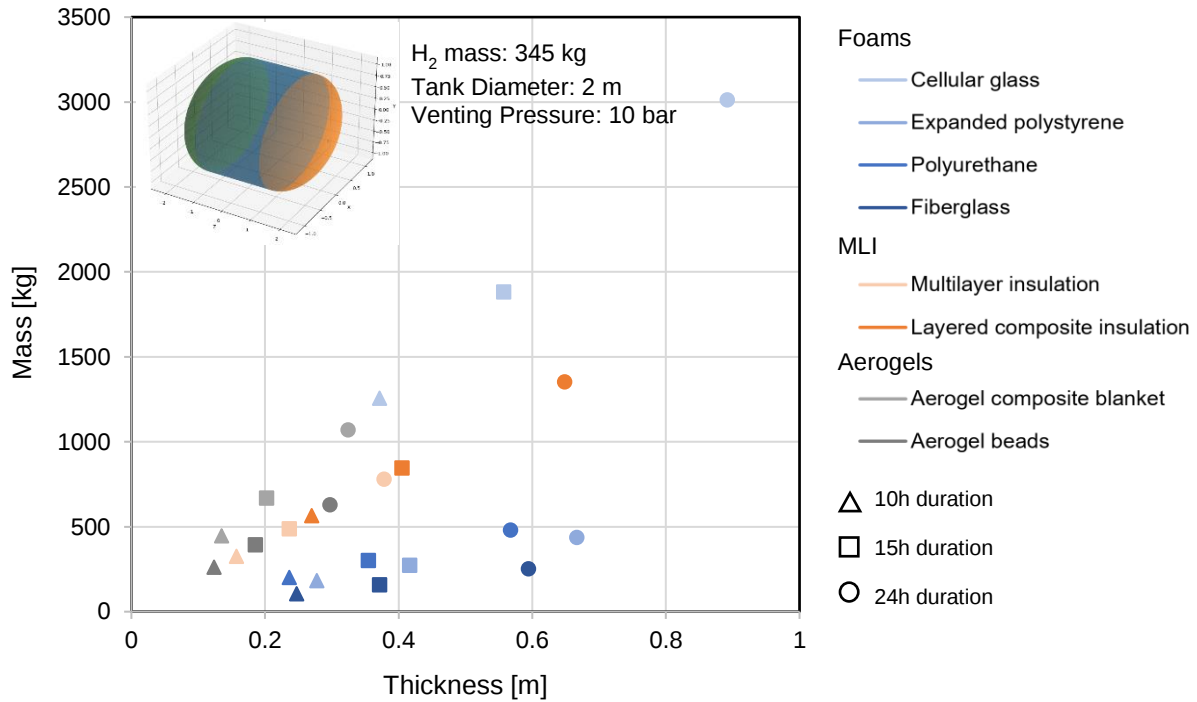


Figure 6 - Mass vs. thickness for different insulation materials

Overall, the thickness necessary to preserve the hydrogen in a liquid state increases with the time of exposure and, therefore, the material's mass. The different insulation materials present similar trends to the materials in their group, except the cellular glass, which displays a higher mass vs. thickness slope, reaching the heaviest scenario, while for the same exposure duration, the other foams display values of around 250 to 500 kg. Aerogels lead to lower thickness but higher mass in comparison with other materials, such as the foams, which display the lowest mass. As the hydrogen stored is 345 kg and the tank used in this test case is 400 kg, an insulation of this order of magnitude is to be considered. Higher mass insulations would not be suitable for aerospace applications.

Figure 6 shows that, except for some foams, none of the insulations are suitable for long-term storage. However, the foam-based insulation needs a thickness of above 0.5 m for a 2 m tank diameter; in a given aircraft fuselage diameter, this would require a longer fuselage, leading to increased aircraft weight and drag. Therefore, tanks with vacuum-based insulation would also need to be considered for tank insulation as they have much lower thermal conductivity than the above-presented materials.

4. Application Cases and Results

The cryogenic tank sizing model presented in Section 3 can be used to explore and evaluate several sizing scenarios for various applications. Each of these scenarios presented in Figure 7 has different objectives and requires different inputs, i.e., for the geometric solver. It has to be noted that the pictures present a notional business jet, and the tank placement is subject to change, considering installation constraints such as engine rotor burst. These and other safety considerations will be further explored once the tank sizing tool is integrated into an MDAO environment. In this section, we will present the capabilities of the tank sizing tool in isolation.

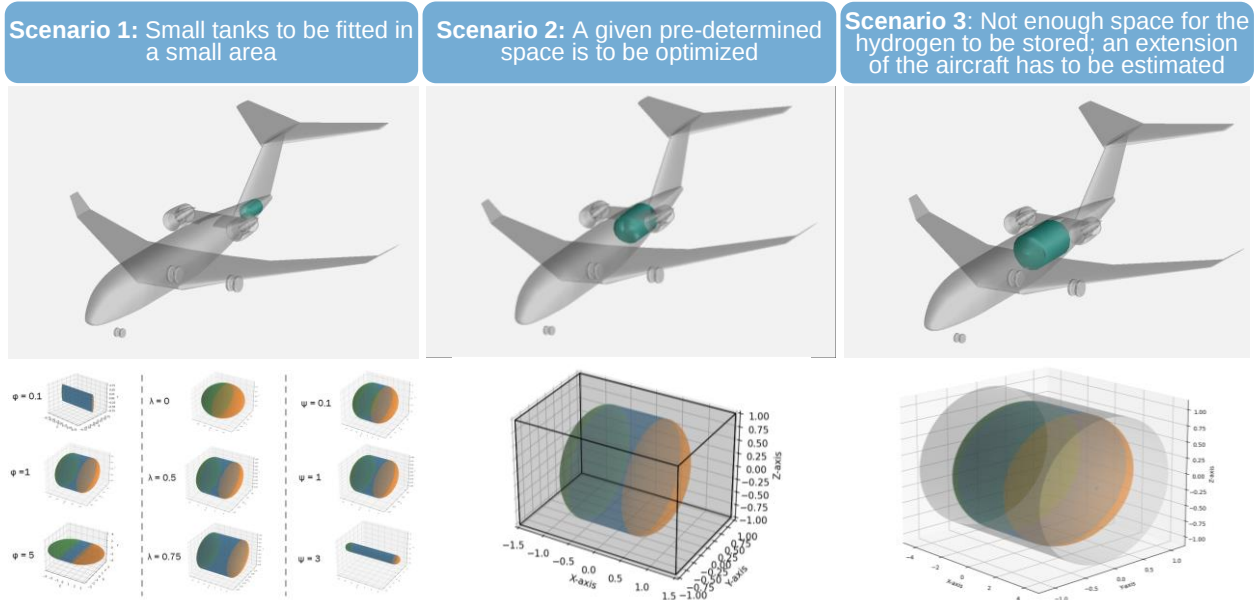


Figure 7 - Tank sizing model application scenarios

Scenario 1 allows the exploration of various shapes based on the geometrical ratios presented in section 3. The geometrical ratios (ϕ , λ , ψ) are varied inputs to allow a freer exploration of versatile tanks. This application case can be used when a small tank is to be fitted into a small or an irregularly shaped area, for example, if an Auxiliary Power Unit (APU) is to be replaced with a hydrogen-powered one or with a hydrogen fuel cell and the tank is to be placed near the tail of the aircraft.

Scenario 2 assumes a pre-defined known allocated space for hydrogen storage. A geometry for a tank that would store the necessary amount of hydrogen while fitting into the pre-determined space is calculated. If the volume of hydrogen to be stored is bigger than the allocated pre-determined volume, then Scenario 3 should be considered.

Scenario 3 is used when a large amount of hydrogen is to be stored, but not enough space is available in the aircraft, and an aircraft extension is needed. The third application case helps determine how long this extension would need to be to accommodate the volume of hydrogen to be stored.

The following sections showcase some test case capabilities of the proposed tool.

4.1 Test Case 1: Variation of tank geometry (excluding insulation)

This test case, corresponding to Scenario 1 above, provides insights into the tank mass variation for varying geometrical ratios, illustrated in Figure 8. It is to be noted that the mass of the insulation is not considered here; but only the mass resulting from the internal geometry sizing and the first tank wall.

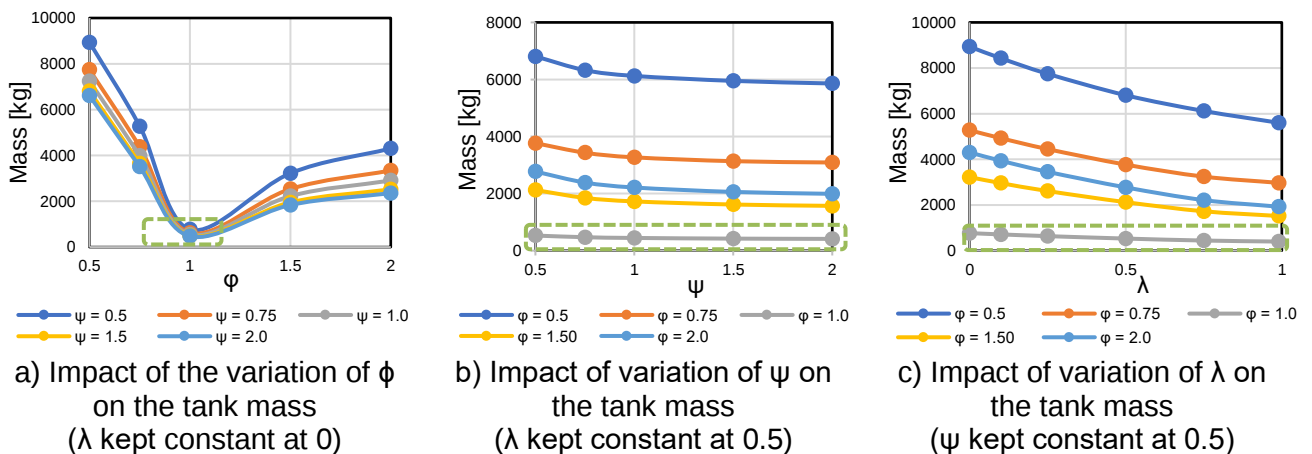
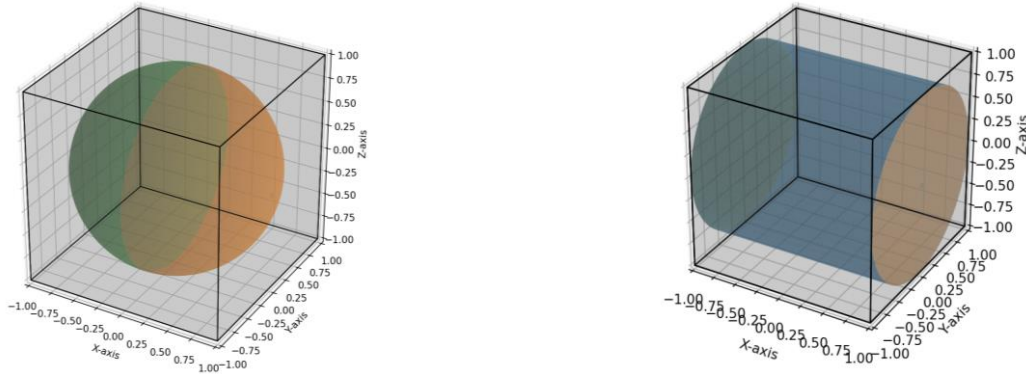


Figure 8 - Impact of geometrical ratios on the tank mass (excluding insulation)

In this case study, the tanks are sized to store 345 kg of hydrogen and a design venting pressure at 1 MPa. The material assumed is aluminum alloy 2219 with a density of 2840 kg/m³ [19]. Figure 8 a) shows that when going further from a value of $\phi=1$, the tank's mass quickly escalates to a range of values unrealistic for aerospace applications. The green rectangle in the plots highlights the feasible regions for further exploration and demonstrates that only values close to $\phi=1$ are truly meaningful. The minimum weight results from tanks with a circular cross-section. Studies assessing the volume taken by these tanks need to be done to conduct trade-off studies on the mass saving vs. the packing efficiency of tanks in a certain space.

4.2 Test Case 2: Tank allocated space

This test case is based on Scenario 2 from above. Given a pre-allocated space for tank storage, the ratio of the tank's volume vs. the volume of the allocated space can be investigated; this is an interesting aspect, as the efficient use of space in an aircraft is of prime importance. Following, trade-off studies of the volume taken by the tank and its mass are possible. A spherical tank would lead to the lowest tank mass for a given allocated space. However, a spherical shape might not lead to the most efficient use of that space. Figure 9 presents an allocated space for the tank (represented by the gray box) in which tanks of different shapes but the same cross-sections are fitted. Subplot a) presents the most efficient shape in terms of mass (a sphere), while subplot b) presents the other extreme - the highest possible usage of the allocated space (a cylindrical tank with flat heads). The former represents 52% usage of the available space, while the latter represents 79% of the available space.



a) Spherical tank in a defined allocated volume b) Cylindrical tank in a defined allocated volume

Figure 9 - Example placement of tank of various shapes in a pre-defined allocated volume

Figure 10 presents the mass of the tank with respect to different volumetric efficiencies. Allocated space for hydrogen storage is defined, and tanks of various volumes and shapes are analyzed with respect to their mass and volumetric efficiency within an allocated volume.

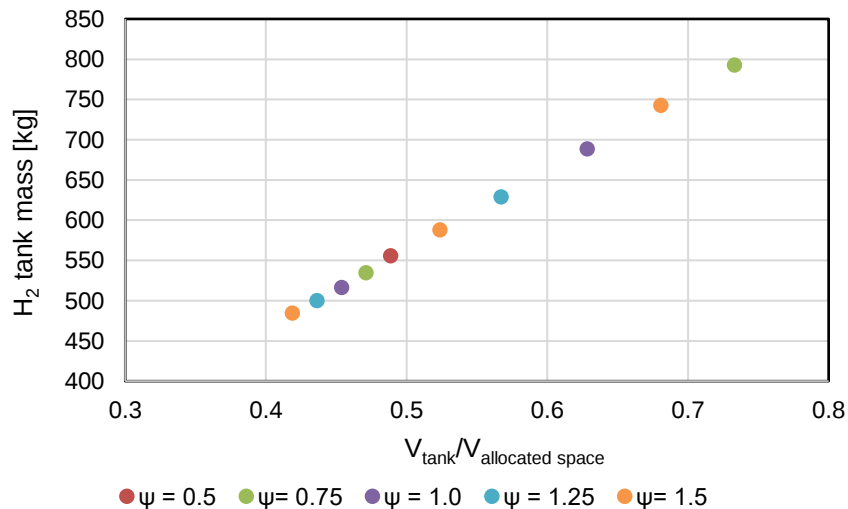


Figure 10 - Tank mass (excl. insulation) for various volumetric efficiencies

Test case 2 illustrates an important capability that will be further explored in an MDAO environment: optimizing the tank configuration with respect to the aircraft-level mass and drag.

4.3 Test Case 3: Tank sizing including insulation (fixed diameter, variable length)

The third test case looks at the change of the insulation and the tank size with respect to the exposure time of the tank to a worst-case scenario of 343.15 K environment. The fuselage diameter is assumed to stay unchanged. The length of the tank can vary depending on the input of other parameters. In this case, the diameter of the tank and the mass of hydrogen to be stored have remained unchanged. The time during which the tank is exposed to heat in-ground was the varied parameter in this study. The configuration presented in Figure 11 is adopted for this case study. The tank is non-integral, with allowance left for the attachment. The tank itself comprises a thin metal wall surrounded by foam insulation. In this test case, the thickness of insulation necessary to keep the hydrogen liquid has been computed, after which the geometry of the tank is recalculated to take into account the space that the thickness of the tank will take away. As the mass of the hydrogen to be stored in the tank stays the same, the bigger the insulation is, and the less space for the tank there is radially, the longer the tank would need to be to store the hydrogen.

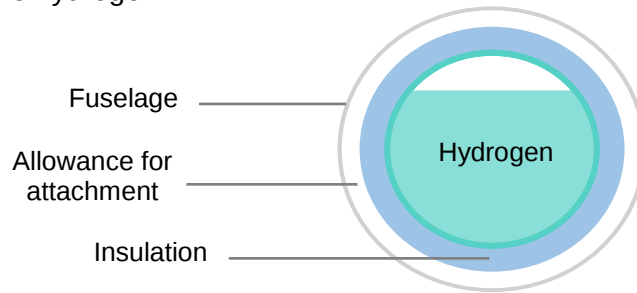
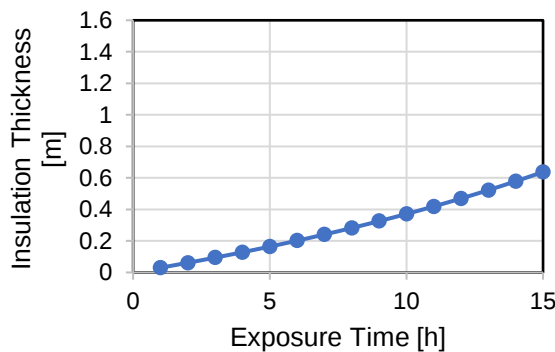
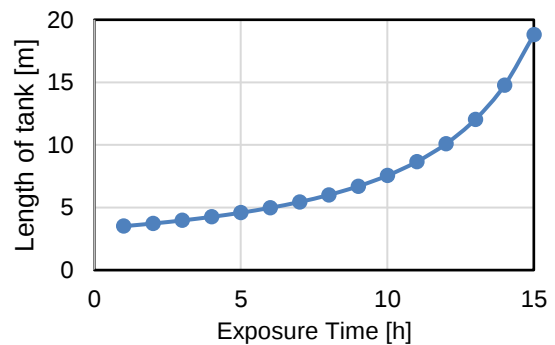


Figure 11 - Fuselage cross-section with inserted hydrogen tank

Figure 12 shows the impact of the exposure time on the insulation thickness and length of the tank. The longer the tank is exposed to a hot environment, the thicker the tank's insulation needs to be; as the tank is contained in the fixed-width airframe of the fuselage and cannot increase radially, the tank length increases with the exposure time.



a) Insulation thickness for different exposure times



b) Length of the tank for different exposure times

Figure 12 - Insulation and tank parameters variation depending on exposure time

4.4 Test Case 4: Multiple tanks with insulation and fixed mass of hydrogen

For safety considerations, more than one tank might be required to store the hydrogen in the aircraft. The presented tool helps to explore different layouts and observe the impact on the system weight and the volumetric efficiency on the tank level; once integrated with an MDAO tool, the tank configuration can be optimized at the aircraft level.

Figure 13 shows the mass of tanks of different layouts containing 345 kg of hydrogen. Five tank layouts are explored and illustrated for transverse and longitudinal cross-sections of a notional fuselage. The tank weights of the multiple small tanks are lower than the unique storage tank weights and are relatively similar to each other. However, the main impact is observed in the insulation weight. The smaller and thinner tanks have a higher surface area to volume ratio and are, therefore, more prone to boil-off. Thicker insulation is thus needed for these tanks. Inversely, in the last layout, the rounder tanks require less insulation than their longer counterparts, while the mass of the tank itself is higher due to a necessary thicker insulation.

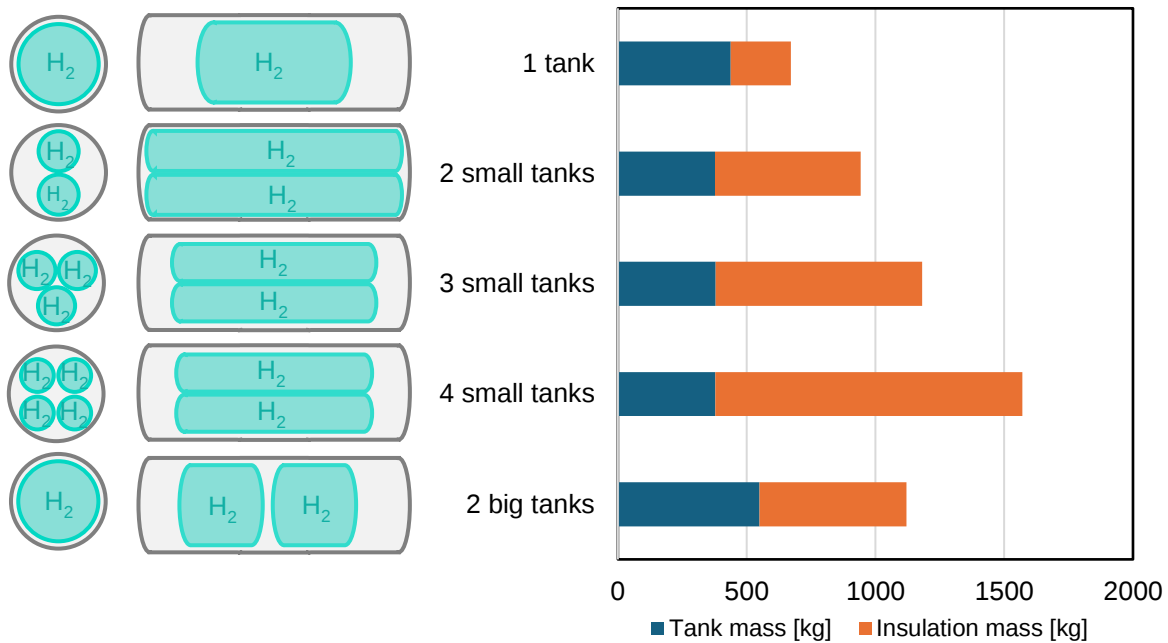


Figure 13 - Tank and insulation weight for different tank layouts

5. Conclusions and Future Work

The test cases showed that, as expected, tanks with circular cross-sections and spherical shapes feature the lowest mass. However, they are not necessarily practical in terms of an efficient usage of the space available to store them. It is, therefore, worth exploring the trade-off between gravimetric efficiency and volumetric efficiency. The model developed allows such trade-off studies. Tank insulation is also to be considered during the sizing process as it significantly impacts the overall weight of the storage system. The insulation mass is impacted by the exposure time of the tank to a hotter environment as well as the size of the tanks. Safety constraints in terms of redundancy and placement should also be considered, as they can impact the storage system's layout and mass. Overall, the presented hydrogen tank storage tool is flexible to evaluate all conceptual design parameters and requirements for conventional and unconventional aircraft configurations.

For future work, the tool will be improved to include multi-layer insulation with vacuum to achieve more realistic insulation thickness. Furthermore, this tank sizing tool will be integrated into an MDAO environment, which can be combined with other tools, such as an aircraft sizing and performance evaluation, life cycle analysis, and the conceptual design tool for particular risk and zonal safety analysis [20]. This will allow the exploration of future aircraft concepts and optimize the hydrogen tank layout on the aircraft level.

In summary, the presented tool helps to evaluate the feasibility of aircraft featuring hydrogen-based propulsion, helping aircraft manufacturers explore concepts that potentially reduce the environmental impact of aviation.

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