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Design and Analysis of Hydrogen Storage Tank for Small Aircraft

Azrayqal Firdaus Zulkeflee[1], Siti Nur Mariani Mohd Yunos[1,*]

[1] Department of Aeronautical Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia

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ABSTRACT

Hydrogen, a chemical element with a high energy density of approximately 120 MJ/kg, presents significant potential as an alternative fuel for aviation. However, its low volumetric density poses a critical challenge, necessitating large storage tanks to accommodate sufficient fuel for practical use. This study aims to design a hydrogen storage system specifically for light aircraft, focusing on the widely used Cessna 172. The proposed design considers evaluating three materials: aluminum, titanium, and steel alloys, under operational pressures of 200 bar and 300 bar. These materials were selected based on their compatibility with existing manufacturing processes to ensure cost-effectiveness. The storage tank features a cylindrical body with spherical domes at both ends to optimize structural integrity and minimize weight. Dimensions are tailored to fit the Cessna 172 cabin, with the tank positioned in the aircraft's rear section. Simulation results using SolidWorks revealed that aluminum alloy 2014-T6, while lightweight, experienced the highest stress, strain, and displacement, requiring reinforcement for high-pressure applications. Titanium Alloy Ti-6Al-4V showed a promising balance between strength and weight, although it is heavier compared to aluminum alloy. On the other hand, Steel Alloy ASTM A514 demonstrated superior strength but was impractically heavy for small aircraft. Overall, the study highlights the limitations posed by the mass of these pressure vessels, emphasizing the need for reinforcements, alternative lightweight materials or composite designs.

1. Introduction

Hydrogen is increasingly recognized as a viable and sustainable energy source for addressing global energy demands, particularly in sectors such as aviation where carbon neutrality is a pressing goal. When produced using renewable energy sources, hydrogen is environmentally friendly, emitting no carbon dioxide during its production or utilization. As a clean fuel, hydrogen produces only water vapor as exhaust, potentially cooling the environment [1]. Its energy density, approximately three times higher than that of conventional jet fuel, makes it a promising candidate for powering short- and medium-range aircraft [2,3]. Ongoing research highlights hydrogen fuel as a promising alternative to conventional aviation fuels, offering a pathway toward sustainable aviation by significantly reducing the environmental impact of air travel and promoting climate change

* *Corresponding author.*
E-mail address: nmariani@uthm.edu.my

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mitigation [1]. Specifically, hydrogen-powered aviation aligns with the International Civil Aviation Organization's (ICAO) targets for carbon-neutral growth and the long-term goal of achieving net-zero aviation emissions by 2050 [4-6].

Despite these advantages, significant research, development, and policy support are needed to implement hydrogen-powered aviation [7,8]. The implementation of hydrogen as an aviation fuel also faces challenges, particularly its low volumetric density and the significant storage space required [3,9]. Under normal temperature and pressure conditions, its volumetric density is 0.084 kg/m^3 compared to the much higher densities of Jet Propellant-8 (800 kg/m^3) or gasoline (750 kg/m^3).

Hydrogen is commonly stored as a liquid under cryogenic conditions at 20.46 K [10] or as compressed gas under high pressure, typically up to 700 bars [11]. Each method has trade-offs: liquid hydrogen achieves higher energy density but introduces complexities in tank design and insulation requirements, while compressed gas presents challenges related to pressure cycling and tank durability [12]. Liquid hydrogen requires complex storage systems to limit boil-off and manage evaporative losses [10]. Conversely, gaseous hydrogen tanks may experience reduced lifespans due to stress caused by variations in pressure and temperature, as well as high storage pressures resulting from numerous refuelling cycles [13]. Additionally, compressed gas storage requires thick-walled containers to withstand the high pressure, making them heavy [11].

When comparing the practicality of gaseous hydrogen and liquid hydrogen for aviation, it is evident that compressed gaseous hydrogen is more suitable for short flights due to its lower volumetric density. This lower density requires larger storage volumes, making compressed gas less efficient for long-distance travel [14]. Conversely, liquid hydrogen is more advantageous for longer flights because it has a higher energy density [15]. However, the challenges are the tank for liquid hydrogen and insulation mass must be minimized [16].

In aircraft, the structural integrity of hydrogen storage tanks is critical, as tanks must be lightweight yet capable of withstanding high pressures and temperature fluctuations without compromising safety [16]. The Cessna 172, one of the most widely used aircraft globally, provides an ideal platform for evaluating hydrogen storage tank designs due to its small size and standardized structure. Designing such tanks to fit within the constraints of aircraft requires careful consideration of dimensions and placement to ensure safety and performance without compromising the aircraft's operational capabilities.

Therefore, this study focuses on designing and analyzing hydrogen storage tanks for small aircraft, specifically targeting models such as the Cessna 172. SolidWorks simulation software was used to compare several materials. This investigation contributes to advancing sustainable aviation technologies by providing insights into material selection, weight limitation, and operational viability. The findings offer an insight into integrating hydrogen fuel storage into light aircraft while supporting global efforts toward cleaner and greener aviation industries.

2. Methodology

2.1 Materials

In this study, we analyzed Type 1 pressure vessels made from three different materials: aluminum alloy 2014-T6 (containing 4.4% Cu), Titanium Alloy Ti-6Al-4V (6% Al, 4% V), and Steel Alloy ASTM A514. The properties for these materials are presented in Table 1. Aluminum Alloy 2014-T6 is a high-strength material with excellent mechanical properties. Aluminum Alloy 2014-T6 is a high-strength material with excellent mechanical properties, making it suitable for applications requiring structural integrity and load-bearing capacity, such as storage tanks. The "T6" designation indicates that the aluminum has been heat-treated and artificially aged to attain its maximum strength. The T6 standard aging process offers the best combination of hardness and corrosion resistance for Aluminum 2014 Alloy, extending its lifespan and reducing maintenance costs in corrosive environments [17]. This material has excellent machinability, allowing for the fabrication of complex shapes and parts, which is advantageous for building a storage tank with specific requirements.

Table 1
Material properties

Materials	Density ($\mathrm{kgm^{-3}}$)	Yield strength (MPa)
Aluminum 2014-T6 (4.4% Cu)	2800	410
Titanium alloy (6% Al, 4% V)	4460	825
Steel (quenched and tempered alloy) ASTM-A514	7820	690

Titanium Alloy Ti-6Al-4V, also known as Grade 5 Titanium, meets various aerospace standards and specifications. It is commonly utilized in structural aircraft components and engine parts due to its high strength, low density, excellent corrosion resistance, and good ductility and toughness [18,19]. This alloy is well-known for its superior performance in demanding aerospace applications. Steel Alloy ASTM A514 is a quenched and tempered alloy steel renowned for its high yield strength and good toughness at low temperatures. Its mechanical properties make it suitable for applications requiring robust structural support. However, due to its higher density compared to Aluminum and Titanium Alloys, weight considerations may affect its practicality for aerospace applications.

2.2 Aircraft

The Cessna 172 Skyhawk was selected for this study primarily because it is one of the most widely used aircraft globally. Since its introduction, the Cessna 172 has been extensively utilized for a diverse range of task such as pilot training, recreational flying, and various commercial applications such as air taxi and charter services [20]. The sizing of the hydrogen storage tank was based on the internal dimensions of the aircraft. The cabin height and width measurements of the aircraft is given in Figure 1. The tank was designed to be positioned in the rear section of the cabin, extending from the rear passenger seat to the baggage area. This placement was chosen to optimize space utilization without compromising the aircraft's operational capabilities or safety.

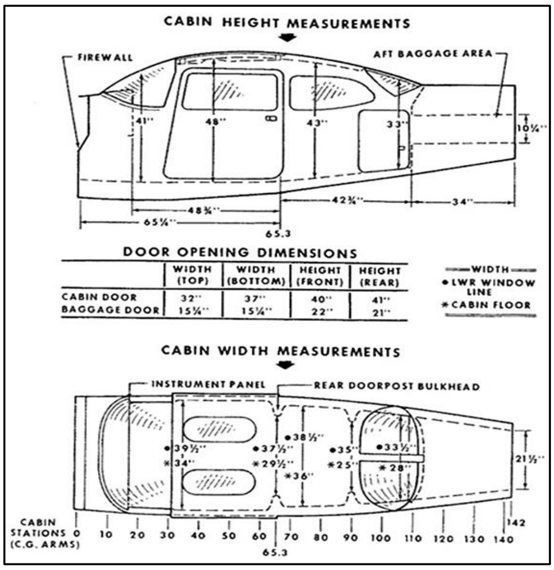

Fig. 1. Cabin height and width measurements of the Cessna 172 [20]

2.3 Determining Tank Mass

As the pressure in the storage increases, the hydrogen gas density will also increase. This relationship is based on ideal gas law for hydrogen gas with compressibility factor, Z. The density and the compressibility factor can be determined using Eq. (1) and Eq. (2), respectively, where P is the gas pressure (Pa), T is the temperature (K), and R is the hydrogen gas constant (4157 Nm/kg.K).

$$\rho = \frac{P}{ZRT} \tag{1}$$

$$Z = 0.99704 + P(6.4149 \ \times 10^{-9}) \tag{2}$$

As the pressure and density increase, the mass of the compressed hydrogen tank will also increase because it needs to withstand the higher pressure. Eq. (3) can be used to calculate the mass of the tank for gaseous hydrogen under pressure, m_h. It is assumed that hydrogen behaves as an ideal gas. Since R for hydrogen has a value of 4157.2 Nm/kg·K, Eq. (3) can be rearranged as shown in Eq. (4).

$$PV = m_h RT \tag{3}$$

$$V = \frac{(4157.2)ZmT}{P} \tag{4}$$

The tank is designed as a cylinder with hemispherical domes on both ends, and the radius, r, can be calculated from the volume obtained in Eq. (4). Further, Eq. (5) is used to calculate the volume of the hemispherical domes and the tank radius. Now that the tank pressure, *P*, and radius, *r*, are known, the required thickness, t, can be determined using the maximum allowable stress, σ, for the selected materials and a factor of safety *(FS)* set at 1.5. Eq. (7) is used to determine the wall thickness for the specified tank. With all the known values, the mass of the tank can be calculated from the wall thickness and the density of the selected materials using Eq. (8).

$$V = \frac{2\pi r^3}{3} \tag{5}$$

$$V = \pi r^2 L \tag{6}$$

$$t = \frac{PrFS}{2\sigma} \tag{7}$$

$$m_t = \rho \left(\frac{4}{3}\right) \pi (r+t)^3 + \pi (r+t)^2 \, L - V \tag{8}$$

2.4 Tank Geometry and Assumptions

Figure 2 presents the front and cross-sectional views of the storage tank, emphasizing the cylindrical structure with spherical domes for optimal pressure distribution. The tank measures 1 meter in length, with outer and inner diameters of 0.5 meters and 0.45 meters, respectively. The idea behind the design is that the aircraft can be equipped with multiple tanks to sustain flight and maximize range. However, the analysis in this study focuses on a single tank to evaluate its structural integrity.

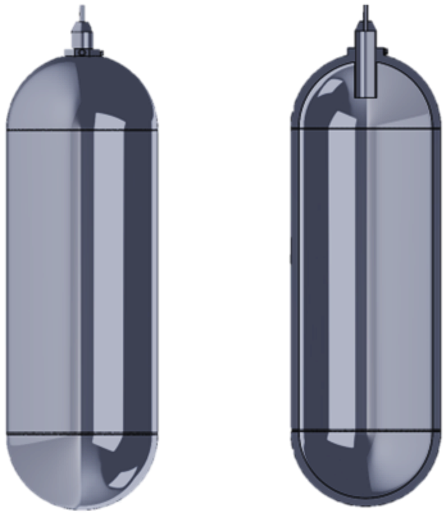

Fig. 2. Tank design (a) Front view (b) Cross-sectional view

In SolidWorks, the tank was split into two parts to separate the top of the tank from its main body. This was done to avoid any complications in the results obtained from the SolidWorks analysis. The motivation behind this design is multifaceted: it is simple to manufacture and easier to inspect and maintain. The cylindrical shape provides a good compromise between volume efficiency and structural stability. It allows for a relatively large internal volume with minimal material usage, making it an efficient design for containing fluids or gases under pressure. Additionally, a cylindrical shape allows for a more uniform distribution of stress throughout the structure. Cylindrical shapes are better suited to withstand internal pressure compared to other shapes because the stress is evenly distributed along the length of the cylinder. The spherical domes on both ends of the cylinder help distribute stress more evenly; the curved shapes of the domes help resist pressure, and their geometry allows for better pressure equalization across the inner surface of the dome.

In this study, the tank was pressurized to 200 and 300 bar. These pressures were chosen as they represent practical and commonly used pressure ranges in compressed hydrogen storage systems. A pressure of 200 bar serves as a baseline for compressed hydrogen storage, while 300 bar allows for greater storage density to extend flight range.

3. Results

3.1 Tank Mass

The masses of tanks made from aluminum alloy 2014-T6 (4.4% Cu), Titanium Alloy Ti-6Al-4V (6% Al, 4% V), and Steel Alloy ASTM A514 (a quenched and tempered alloy) were compared in this study (Table 2). The comparison of these materials focuses on their potential use in the construction of hydrogen storage tanks for small aircraft like the Cessna 172.

Table 2
Tank mass at pressures of 200 and 300 bar

Materials	Total mass (kg) (200 bars)	Total mass (kg) (300 bars)
Aluminum 2014-T6 (4%Cu)	126.69	128.35
Titanium alloy (6% Al, 4% V)	198.45	200.11
Steel aloy ASTM-A514	342.57	344.23

At room temperature, when the tank was pressurized to 200 bars, the mass of hydrogen was approximately 3.33 kg, and the volume of the tank was 0.207 m³. Due to the hydrogen compressibility effect, the change in pressure in the tank did not influence the mass of the tank itself. When the tank was pressurized to 300 bars, the volume of the tank remained at 0.207 m³, while the mass of hydrogen gas increased to approximately 4.99 kg.

3.2 Tank structure

To evaluate the tank structure, four parameters: von Mises stress, first principal stress, strain, and displacement, were analysed when the tank was subjected to a pressure of 200 bar and 300 bar. The analyses were conducted using SolidWorks simulation software. The results are presented in Table 3. Each material demonstrated distinct performance characteristics that influence its suitability for hydrogen storage tank applications.

Von Mises stress measures the overall stress level within the material and determines whether the material will yield under applied pressure. It can be observed that aluminum alloy 2014-T6 shows higher values compared to Titanium Alloy Ti-6Al-4V and Steel Alloy ASTM-A514, reflecting its lower yield strength. At 300 bar, maximum stresses in the aluminum alloy 2014-T6 exceed the material's yield strength, particularly at the top dome, suggesting a higher risk of permanent deformation under extreme pressure. To compensate for this, specialized materials and design modifications at the entry point are necessary to reinforce the tank's structural integrity in that area. Titanium Alloy Ti-6Al-4V showed moderate stress levels, indicating better resistance to deformation, while Steel Alloy ASTM-A514 showed the lowest Von Mises stress due to its high yield strength. The results highlight the ability of Steel Alloy ASTM-A514 to handle high pressures without yielding, but it comes at the cost of higher weight.

Table 3
Comparison between the three selected materials

Material	Parameters	200 Bar		300 Bar	
		Minimum	Maximum	Minimum	Maximum
Aluminum alloy 2014-T6	Von Mises (N/m^2)	$7.615\ x\ 10^4$	$4.541\ x\ 10^8$	$1.283\ x\ 10^5$	$6.785x\ 10^8$
	1st principal (N/m^2)	$1.038\ x\ 10^7$	$4.848\ x\ 10^8$	$-1.574\ x\ 10^7$	$7.224\ x\ 10^8$
	Strain	$7.378\ x\ 10^{-7}$	$4.241\ x\ 10^{-3}$	$1.126x\ 10^{-6}$	$6.388\ x\ 10^{-3}$
	Displacement (mm)	0.1458	0.6495	0.2193	0.9641
Titanium alloy Ti-6Al-4V	Von Mises (N/m^2)	$5.191\ x\ 10^4$	$4.520\ x\ 10^8$	$6.764\ x\ 10^8$	$6.764\ x\ 10^8$
	1st principal (N/m^2)	$-9.889\ x\ 10^6$	$4.815\ x\ 10^8$	$-1.471\ x\ 10^7$	$7.189\ x\ 10^8$
	Strain	$4.932\ x\ 10^{-7}$	$2.878\ x\ 10^{-3}$	$7.221\ x\ 10^{-7}$	$4.306\ x\ 10^{-3}$
	Displacement (mm)	0.1043	0.4582	0.1569	0.6821
Steel alloy ASTM-A514	Von Mises (N/m^2)	$3.966\ x\ 10^4$	$4.486\ x\ 10^8$	$6.893\ x\ 10^4$	$6.721\ x\ 10^8$
	1st principal (N/m^2)	$-9.321\ x\ 10^6$	$4.76\ x\ 10^8$	$-1.378\ x\ 10^7$	$7.125\ x\ 10^8$
	Strain	$2.373\ x\ 10^{-7}$	$1.397\ x\ 10^{-3}$	$3.431\ x\ 10^{-7}$	$2.092\ x\ 10^{-3}$
	Displacement (mm)	0.0549	0.2352	0.08198	0.3153

The range of first principal stress values is considerable for the three materials, indicating the presence of both tensile and compressive stresses. This is due to the presence of a tube which serves as the entry point for the gas and accommodates the temperature sensor mounting (usually applied to liquid hydrogen) at the top of the hemispherical dome. This configuration means that the force acting from inside the tube is in the opposite direction when the analysis in SolidWorks is conducted, introducing curvature and slight changes in geometry that affect the stress distribution. This tube cannot be excluded from the analysis because it is located inside the tank, which is crucial. If the pressure valve and related components are included in the SolidWorks analysis, the minimum and maximum stress values may interfere with the analysis of the tanks, leading to inaccurate determinations of the structural integrity of the pressure vessel. Therefore, materials with higher von Mises stress and first principal stress must be highlighted in applications where strength is crucial.

Higher first principal stress values were observed in the aluminum alloy 2014-T6, indicating additional structural reinforcement is required for its application in high-pressure scenarios. Titanium Alloy Ti-6Al-4V demonstrated moderate principal stress levels, showcasing its ability to handle pressure effectively while maintaining structural stability. Steel Alloy, with the lowest principal stress, performed best in minimizing tensile and compressive stresses, further reinforcing its structural robustness.

In terms of strain, the results provide insight into the ductility of the selected materials. By comparing all the materials, aluminum alloy 2014-T6 exhibits the highest values, indicating it can withstand greater deformation before failure, suggesting a more ductile behaviour. Titanium Alloy displayed lower strain values, striking a balance between flexibility and rigidity. Steel Alloy ASTM-A514, with the lowest strain, confirmed its stiffness and minimal deformation under applied loads, making it ideal for applications requiring high rigidity and dimensional stability.

The variation in displacement values highlights the material stiffness and flexibility under applied pressure. Materials such as Steel Alloy ASTM A514 may be considered stiffer, while aluminum alloy 2014-T6 can be considered more flexible when comparing the displacements. Titanium alloy Ti-6Al-4V exhibited moderate displacement, suggesting better control of deformation while maintaining some flexibility.

3.3 Discussion

The materials demonstrated the capability to withstand such high pressures; however, the resulting tank weight poses a disadvantage when compared to Type IV pressure vessels. Aluminum alloy 2014-T6 is lightweight and ductile, making it suitable for applications prioritizing weight reduction. However, its higher stress, strain, and displacement values under pressure limit its effectiveness for high-pressure storage without reinforcements. Steel Alloy ASTM-A514 excels in stress resistance and dimensional stability, but its high density is impractical for small aircraft.

Utilizing aluminum alloy 2014-T6 or Titanium Alloy Ti-6Al-4V appears viable in terms of weight considerations, but the low volumetric density of compressed hydrogen gas makes using a single pressure vessel impractical for the Cessna 172. Compressed hydrogen at 70 MPa has a significantly lower volumetric density compared to liquid hydrogen, which is approximately 38 kg H_2/m^3 (equivalent to 5.6 MJ/L).

Storing sufficient hydrogen for practical flight durations would require multiple or larger pressure vessels, increasing the weight beyond acceptable limits. Given that the Cessna 172 has a maximum take-off weight of 1,157 kg and a maximum payload of 395 kg, adding heavy pressure vessels is not feasible. Therefore, despite the materials' ability to withstand the required pressures, the use of Type 1 pressure vessels for hydrogen storage in small aircraft like the Cessna 172 is not practical due to weight constraints.

The 200-bar pressure serves as a baseline foe low-pressure hydrogen storage tank, while 300 bar pushes the boundary towards higher pressure storage tank to provide insights for future design improvements. These pressures reflect the trade-offs that need to be addressed for small aircraft applications.

4. Conclusions

This study focused on the design and analysis of hydrogen storage tanks for small aircraft, specifically targeting the Cessna 172. Three materials were evaluated namely aluminum alloy 2014-T6, Titanium Alloy Ti-6Al-4V, and Steel Alloy ASTM A514. Using SolidWorks simulation software, the tanks were analysed under pressures of 200 bar and 300 bar to determine parameters such as von Mises stress, first principal stress, strain, and displacement. All three materials demonstrated their capability to withstand high pressures.

Aluminum alloy 2014-T6 is best suited for applications requiring lightweight materials, but it is less ideal for high-pressure tanks unless reinforced. Titanium Alloy Ti-6Al-4V showed a promising balance between strength and weight, making it suitable for high-pressure applications. On the other hand, Steel Alloy ASTM A514 excelled in strength but was too heavy for practical use in small aircraft.

The study also highlighted that the mass of the tanks made from these materials poses a significant disadvantage for small aircraft like the Cessna 172. The added weight of the pressure vessels is excessive for the aircraft, making their implementation impractical. Future research should explore alternative storage methods, such as lightweight composite materials or different pressure vessel types, consider adding reinforcement or applications in larger aircraft where weight limitations are less restrictive.

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