Analysis of Insulation Materials for Cryogenic Hydrogen Storage Tank for Light Aircraft

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Abstract

This study investigates the influence of insulation material on the performance of a cryogenic hydrogen storage tank designed for a light aircraft. A cylindrical pressure tank with hemispherical end domes was sized for integration into the aft cabin of a Cessna 172 aircraft. The tank and insulation layers were modeled in SolidWorks 2022. Static structural and steady-state thermal analyses were performed for fiberglass and aerogel as the insulation materials. The mass characteristics, stress distribution, and thermal behavior of the two configurations were compared. For the same storage pressure and volume, the total mass of the fiberglass-insulated tank was about 38.9 kg, whereas the aerogel-insulated tank had a reduced total mass of approximately 15.9 kg, representing a reduction of more than 50% in the system mass. In both cases, the von Mises stress field was dominated by the cylindrical shell, with lower stresses in the domes, and no adverse stress concentrations were introduced by replacing the fiberglass with aerogel. Thermal analysis indicated that the fiberglass configuration developed a higher heat flux and significant temperature gradients, leading to an estimated hydrogen boil-off rate of 2019.2 g/h. By contrast, the aerogel configuration maintained most of the internal surface close to the cryogenic temperature, with a much lower heat flux of 0.2223 W/m^2, a total heat transfer rate of 0.2223 W, and a boil-off rate of only 3.6 g/h. These findings indicate that aerogel offers substantial advantages over fiberglass for cryogenic hydrogen storage in light aircraft. Therefore, it merits further investigation in more detailed tank- and aircraft-level design studies.

1. Introduction

Aviation operations contribute approximately 2.5% of global CO_2 emissions, a figure projected to grow substantially without significant technological interventions. Consequently, the International Civil Aviation Organization (ICAO) has established aggressive carbon reduction targets, committing to net-zero CO_2 emissions by 2050. This ambitious goal necessitates the development of alternative propulsion technologies and sustainable fuels (IPCC, 2023).

Among the promising sustainable alternatives, hydrogen stands out as a clean energy carrier with a high energy density per mass, positioning it as a key candidate for future aviation fuels (Boretti, 2024; Brewer, 2017). Hydrogen is the most abundant element in the universe and is non-toxic and odorless. However, integrating hydrogen into aircraft presents significant design and engineering challenges, particularly concerning its storage. Unlike conventional jet fuel, which is stored under ambient conditions, liquid hydrogen must be kept at an

extremely low temperature of -253°C (20 K) to remain in liquid form owing to its low ambient density (Abdalla et al., 2018).

This necessitates sophisticated cryogenic storage systems, which significantly affect aircraft weight and volume allocation, especially for light aircraft with limited onboard space (Burschyk et al., 2023). One of the foremost technical challenges is minimizing heat transfer to cryogenic hydrogen to reduce boil-off. Uncontrolled boil-off leads to substantial energy loss and increased operational expenses. Consequently, highly efficient thermal insulation is essential to ensure the viability and safety of hydrogen-powered aircraft (Abdalla et al., 2018; Morales-Ospino et al., 2023).

Boil-off hydrogen (BOH) occurs because of the evaporation of liquid hydrogen, mainly due to heat entering the storage tank. Although several mitigation strategies exist, in many scenarios, vented hydrogen is lost to the atmosphere, causing further waste and safety concerns (Morales-Ospino et al., 2023). Therefore, advanced insulation materials and tank designs are essential for maintaining thermal stability in cryogenic hydrogen storage and minimizing hydrogen boil-off (Yatsenko et al., 2022). Insulation types such as foam, fiberglass, aerogel, multi-layer insulation (MLI), and hollow glass microspheres (HGMs) have been researched for their superior thermal performance, low density, lightweight characteristics, vacuum sensitivity, and suitability for aerospace applications (Mital et al., 2006). However, comprehensive research evaluating their comparative performance specifically for cryogenic hydrogen use in aircraft operating environments is limited.

Therefore, this study aims to fill the gaps in the literature by evaluating the thermal performance of fiberglass and aerogel insulation materials applied to a cryogenic hydrogen storage tank designed for a light aircraft, specifically the Cessna 172 aircraft. Using SolidWorks simulations, the temperature distribution, heat flux, and estimated hydrogen boil-off rates under steady-state thermal loads were investigated.

2. Methodology

2.1 Aircraft Selection and Tank Integration

The Cessna 172 Skyhawk was selected as the reference aircraft. It is widely used in general aviation and has publicly available, well-documented geometric and performance characteristics, which simplify the conceptual integration of additional systems. The hydrogen tank was assumed to be installed in the aft cabin region, spanning from the rear passenger seats to the baggage compartments. This location was selected because of the ease of access and the availability of usable volume without major structural modifications to the main airframe. The cabin dimensions of the Cessna 172 (Figures 1 and 2) were used as geometric constraints for the tank length and diameter. The design assumes that multiple tanks of identical geometry can be installed in parallel for an extended range if required. However, only a single tank was modeled and analyzed in this study.
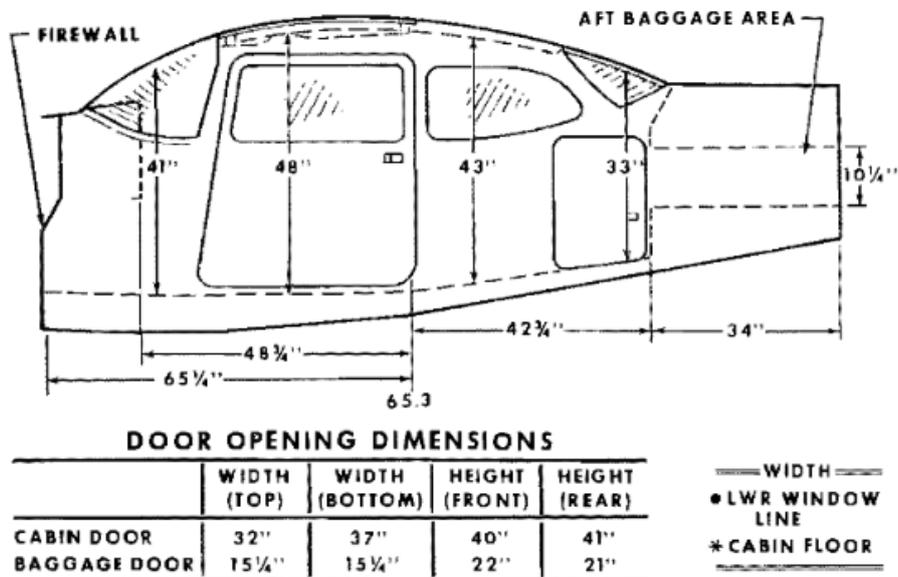

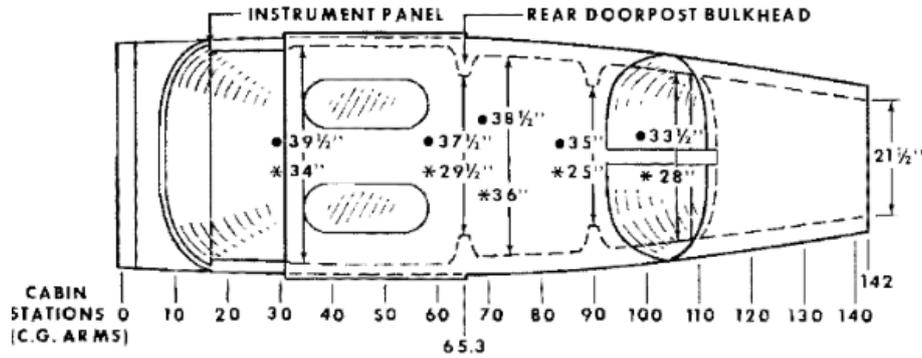**Fig. 1** *Cabin height measurement*

Fig. 2 *Cabin width measurement*

2.2 Hydrogen Storage Conditions

The storage system considered in this study is a compressed gaseous hydrogen tank intended to operate at high pressures. This configuration is suitable for short-range missions and represents a practical first step towards hydrogen integration in general aviation. Hydrogen in the tank was treated as a real gas and approximated using the ideal gas equation of state:

$$PV = m_h RT \tag{1}$$

where P is the storage pressure, V is the storage volume, T is the storage temperature, R is the specific gas constant for hydrogen (4157.2 Nm/kg. K), and m_h is the mass of hydrogen gas. The equation of state also allows the required internal volume to be estimated for a specified storage pressure and mass of hydrogen.

In this study, the tank was sized to contain compressed hydrogen at a nominal storage pressure of 200 bar. The resulting internal volume obtained from these calculations was used to define the tank geometry. The hydrogen was assumed to remain in a compressed state at cryogenic temperatures throughout the analysis. Phase change phenomena and detailed thermodynamic modeling of boil-offs are not explicitly represented in the sizing step.

2.3 Tank Geometry and Wall Thickness

The storage vessel was modeled as a cylindrical shell with hemispherical end domes. This configuration is commonly used for pressure vessels because it achieves a favorable distribution of stresses, minimizes local stress concentration at the ends, and maximizes the usable internal volume for a given overall length. The tank geometry is presented in Table 1.

Table 1 *Geometry of the hydrogen tank*

Parameter	Length
Total tank length (including domes)	1.00 m
Outer diameter	0.50 m
Inner diameter	0.45 m

The internal volume, V_{tank}, is obtained by combining the cylindrical volume and the volumes of the two hemispherical ends as follows:

$$V_{tank} = \pi r^2 L + \frac{4}{3}\pi r^3 \tag{2}$$

where r is the inner radius of the tank and L is the length of the cylindrical section. Once the internal radius, r, and design pressure, P, are known, the wall thickness of the pressure vessel, t, is estimated using a cylindrical thin-wall pressure vessel formula with an imposed factor of safety, FS, of 1.5:

$$t = \frac{PrFS}{\sigma_{allow}} \tag{3}$$

where σ_{allow} is the allowable stress for the selected structural material. This approach was applied to the cylindrical section, while the same thickness was conservatively adopted for the hemispherical domes. The structural mass of the tank, m_{tank}, is then calculated from the volume of the shell material (difference between the outer volume, V_{outer}, and inner volume, V_{inner}) and the density of the material, $\rho_{material}$:

$$m_{tank} = \rho_{material}(V_{outer} - V_{inner}) \tag{4}$$

These calculations provided an initial estimate of the tank mass, which was subsequently refined using the SolidWorks model.

2.4 Insulation Materials

The insulation materials selected for this study were fiberglass and aerogel. These materials are well-established thermal insulators, each with distinct properties suitable for cryogenic hydrogen storage. Fiberglass is a conventional fiber-based insulation commonly used in industrial applications owing to its moderate thermal conductivity and mechanical robustness. Aerogel, by contrast, is a highly porous insulation and noted for its ultra-low thermal conductivity and low density, which make it particularly advantageous for weight-sensitive aerospace applications. The relevant physical and thermal properties of these materials were obtained from publicly available literature and manufacturer datasheets and are summarized in Table 2.

Table 2 *Physical and thermal properties of the insulation materials*

Property	Fiberglass	Aerogel
Density (kg/m^3)	25	200
Specific heat capacity (J/kg.K)	800	700
Thermal conductivity (W/m.K)	0.032-0.040	0.015

2.5 Modelling Approach

All geometric modelling and numerical analyses were performed using SolidWorks 2022. The tank, including its structural shell and insulation layer, was constructed as a three-dimensional solid model. Standard SolidWorks solid elements with automatic mesh refinement were used in the analysis. The hydrogen was not explicitly meshed as a fluid domain. Instead, it is represented via the internal pressure load and thermal boundary conditions at the inner wall.

The structural performance of the tank was assessed using static pressure analysis in SolidWorks. The internal surface of the tank was subjected to a uniform internal pressure corresponding to a design condition of 200 bar, representing the maximum operating pressure of the compressed hydrogen. A safety factor of 1.5 was applied to the wall thickness design, as described previously. The structural analysis outputs were compared with the allowable material limits to judge whether the tank design was structurally adequate.

The thermal performance of the cryogenic tank was evaluated by imposing a thermal load representative of heat ingress during aircraft operations. The initial temperature of the tank interior was set to approximately −253°C, corresponding to the cryogenic temperature of liquid hydrogen or deeply cooled gaseous hydrogen. A total heat load of 250 W was applied in the SolidWorks thermal simulation to represent the combined effects of external heat transfer mechanisms (such as convection, radiation, and conduction from the surrounding environment).

3. Results and Discussion

3.1 Mass Characteristics of the Tank

Based on the geometric dimensions specified in the methodology, SolidWorks was used to obtain the masses of each major component of the tank. For both insulation options, the mass of the structural layer was about 10.39 kg, and the internal volume was fixed at approximately 0.207 m^3, which is sufficient to store compressed hydrogen at 200 bars with an estimated hydrogen mass of about 3.33 kg. Figure 3 shows the tank mass when the insulation layer was applied.

For the configuration with fiberglass insulation, the insulation layer contributed 25.5 kg to the total mass of the tank. The total mass of this configuration was approximately 38.9 kg. In the implemented configuration, the mass of the aerogel insulation layer is 2.07 kg compared with 25.5 kg for fiberglass, due to the combination of the chosen thickness and material definition in the SolidWorks model. When combined with the same hydrogen mass (3.33 kg), the total mass of the aerogel-insulated configuration was reduced to about 15.9 kg. Thus, for an identical

internal volume and operating pressure, replacing fiberglass with aerogel lowers the overall tank system mass by roughly 23 kg.
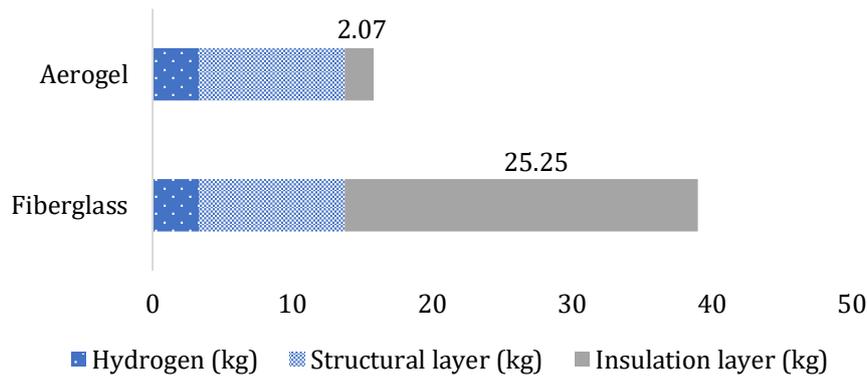

Fig. 3 *Tank mass with insulation layer*

This difference is significant from an aircraft integration perspective. A reduction of more than 50% in the tank system mass directly translates into an increased useful payload or range, especially in small aircraft such as the Cessna 172. It also eases the management of the center of gravity when the tank is placed in the aft cabin region.

3.2 Structural Response under Internal Pressure

Structural analysis was performed for both insulation configurations at an internal pressure of 200 bar. The aim was to assess whether the tank geometry and wall thickness determined by the methodology could withstand the applied pressure and whether the change in insulation material had any effect on the stress. This study only focused on stress as the structural metric, and the results are summarized in Table 3.

Table 3 *Structural analysis results of fiberglass and aerogel insulated tanks*

Property		Fiberglass	Aerogel
von Mises Stress (N/m^2)	Min	1.52×10^4	9.64×10^1
	Max	5.66×10^8	4.09×10^8

The von Mises stress distribution for the tank with a fiberglass insulation layer indicates that the lowest stresses occur near the top and bottom domes, whereas the highest stresses are concentrated in the cylindrical mid-section. The dome experiences lower stress levels because the curvature allows a more uniform distribution of internal pressure, whereas the cylindrical section experiences higher hoop stress. When the fiberglass outer layer is replaced by aerogel, the structural behavior remains qualitatively similar because the primary load-bearing structure remains unchanged. However, the change in external stiffness and mass distribution leads to slightly different stresses.

Overall, the stress pattern remained dominated by the cylindrical section in both configurations, and adding aerogel as an insulation layer did not introduce unfavorable stress concentrations in the structural shell. However, a more detailed structural design would require revisiting to ensure that the displacements and strains remain within physically realistic bounds.

3.3 Thermal Behavior and Insulation Performance

Thermal analyses were carried out for an initial internal temperature of −253°C and a constant thermal load of 250 W imposed for 600 s. The key quantities of interest are the thermal gradients, heat flux through the tank wall, total heat transfer rate, and the resulting hydrogen boil-off rate. A summary is presented in Table 4.

Table 4 *Thermal analysis results of fiberglass- and aerogel-insulated tanks*

Property	Fiberglass	Aerogel
Thermal gradient (°C)	7.7	17.1
Heat flux (W/m^2)	15.4	0.2223
Total heat transfer rate (W)	30.8	0.2223

Boil-off rate (g/h)	2019.2	3.6

For the fiberglass-insulated tank, the temperature field after 600 s showed noticeable spatial variation. These values correspond to different locations on the tank, with colder regions typically found in sections more shielded from the applied heat load and warmer regions near the dome surfaces, where the geometry is more exposed. The dome regions also tend to warm more rapidly than the central portions of the cylinder. Notably, the thermal model uses a simplified representation of the external environment and does not explicitly model the multi-layer insulation or detailed venting behavior. Nevertheless, even with these simplifications, the fiberglass configuration clearly allows a relatively high heat flux across the tank wall, which is reflected in the large boil-off rate.

The aerogel-insulated tank exhibited a significant thermal response. The temperature distribution shows that most of the internal surface remained close to the initial cryogenic temperature. The recorded minimum temperature was approximately −253.5°C, which is the target storage temperature for liquid hydrogen. This indicates that the aerogel layer is highly effective in restricting heat penetration, as the cold region inside the tank remains almost uniform, with very limited warming of the hydrogen boundary. Furthermore, the heat flux, total heat transfer rate, and boil-off rate were significantly lower than those observed for the fiberglass configuration.

3.4 Discussion

The combined mass, structural, and thermal results provide a coherent picture of the relative performance of fiberglass and aerogel as insulation materials for a cryogenic hydrogen storage tank in a small aircraft. In terms of mass, aerogel reduces the total system mass at 200 bars from about 38.9 kg (fiberglass) to 15.9 kg, primarily due to its much lower density. For a small aircraft, this is a substantial weight-saving effect. From a structural standpoint, both configurations showed similar stress patterns, with the cylindrical shell exhibiting the highest von Mises stress and the domes exhibiting a more uniform stress distribution. The change in insulation material has only a secondary influence on the stress levels, which remain of the same order of magnitude in both cases. A comparison of the thermal performance shows that the fiberglass-insulated tank allows significant heat ingress, leading to large thermal gradients and very high estimated boil-off rates. In contrast, aerogels provide excellent thermal insulation, maintaining internal temperatures close to −253°C and significantly reducing the boil-off rate. In summary, within the assumptions and simplifications of this study, aerogels emerge as the more promising insulation material for cryogenic hydrogen storage tanks in light aircraft. It offers a lower mass, better temperature maintenance, and much lower boil-off, all of which are essential for integrating hydrogen systems into weight-sensitive aircraft. For future work, it would be valuable to validate the thermal model against experimental or higher-fidelity data and refine the structural analysis with a convergence study and clearer safety margins.

4. Conclusion

This study investigated the suitability of fiberglass and aerogel as insulation materials for a cryogenic hydrogen storage tank concept integrated into a Cessna 172 light aircraft. A cylindrical pressure vessel with hemispherical end domes was sized to store compressed hydrogen at 200 bar, yielding an internal volume of approximately 0.207 m³ and a hydrogen mass of approximately 3.33 kg. The tank and insulation layers were modeled using SolidWorks 2022, and the structural and thermal responses were evaluated using static pressure and steady-state thermal analyses.

The results indicate that the choice of insulation has a pronounced effect on both the system's mass and thermal performance while only modestly influencing the structural stress pattern. For the same internal volume and storage pressure, the total mass of the fiberglass-insulated configuration was about 38.9 kg, whereas the aerogel-insulated configuration had a reduced total mass of approximately 15.9 kg. This reduction of more than 50% in the tank system mass is highly beneficial for light aircraft, where the weight and center-of-gravity margins are tightly constrained. In both configurations, the von Mises stress distribution was dominated by the cylindrical shell, with lower stresses in the domes, consistent with the classical pressure-vessel behavior. No unfavorable stress concentrations were introduced by replacing the fiberglass with aerogel in the present model. Thermal analysis revealed significantly larger differences between the two insulation materials. Under a 250 W applied thermal load and an initial internal temperature of −253°C, the fiberglass-insulated tank exhibited a relatively high heat flux and significant temperature gradients, leading to an estimated hydrogen boil-off rate of 2019.2 g/h. In contrast, the aerogel-insulated tank maintained most of the internal surface close to the cryogenic temperature, with a greatly reduced heat flux of 0.2223 W/m², a total heat transfer rate of 0.2223 W, and a corresponding boil-off rate of only 3.6 g/h. These results suggest that aerogels can reduce the boil-off by several orders of magnitude for the studied configuration.

Within the assumptions and simplifications of this study, aerogels emerge as highly promising insulation materials for cryogenic hydrogen storage tanks in light aircraft, combining a lower system mass with superior thermal performance. Future work should focus on refining the structural model for low-stiffness insulation

layers, exploring multilayer insulation concepts, validating the thermal predictions against experimental data or higher-fidelity simulations, and assessing aircraft-level impacts such as range and payload.

Acknowledgement

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm their contribution to the paper, as follows: **study conception and design:** *Muhammad Aiman Hakimi Nazri, Siti Nur Mariani Mohd Yunos;* **data collection, analysis, and interpretation of results:** *Muhammad Aiman Hakimi Nazri;* **draft manuscript preparation:** *Muhammad Aiman Hakimi Nazri, Siti Nur Mariani Mohd Yunos. All the authors reviewed the results and approved the final version of the manuscript.*

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