Overview of the Challenges in High-Pressure Type V Hydrogen Tanks for Automotive Applications

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Abstract. Hydrogen emerges as a pivotal element in achieving fossil-free transportation, offering a sustainable alternative to conventional fossil fuels and significantly reducing environmental impacts. This report outlines the development of a cutting-edge Type V high-pressure vessel employing carbon fiber composite material, aimed at tackling the challenges associated with liner less hydrogen pressure vessel. Current research focuses on addressing two major challenges, namely manufacturing complexity and leak tightness of the tank. Manufacturing complexity of the tank is thoroughly addressed, covering various removable mandrel technologies and further a novel integral mandrel technique is introduced, featuring a carbon fiber-reinforced polymer (CFRP) structure.

Another significant challenge is ensuring the leak tightness of the tank without a polymer liner. The current article explains this issue in detail and discusses various solutions for a liner less, leak-tight tank structure. While Type V pressure vessels offer advantages in weight and storage capacity, their integration into automotive applications requires addressing manufacturing complexity, leak tightness, material compatibility, and cost-effectiveness. By overcoming these obstacles, the full potential of Type V tanks in hydrogen vehicles for the transportation sector can be realized, fostering sustainable mobility solutions.

Keywords: Filament winding · Type V pressure vessels · Permeability First Section

1 Introduction

The automotive industry is integrating futuristic research and focusing on sustainability, autonomous driving, smart connectivity and electric and hydrogen powered vehicles. The development of hydrogen fuel cell vehicles can enhance safety, efficiency and sustainability of the transportation sector. According to the Global EV outlook 2023 report, the number of hydrogen based vehicles has increased by 40% in 2022 [1]. Although hydrogen offers a clean energy source and high energy efficiency, the safe and compact storage is a significant factor to consider in order to replace the fossil fuels completely. As part of the DigiTain research project, a high pressure hydrogen composite overwrapped pressure vessel is being developed in compliance with EU Regulations No. 134 [2, 3].

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Lightweight and high strength pressure vessels are widely used in various sectors like aviation, space and transportation etc. The evolution of the various types of pressure vessels has been a focus of research throughout decades [4]. The initial versions (Type I-III) had a significant metal component in it. Type I completely made up of metal, Type-II is metallic with composite hoop-wrapped and Type-III is completely composite overwrapped on a metallic liner. In the case of Type IV, the fuel is stored in a plastic liner which also serves as a mandrel for the filament winding process. The latest Type V technology offers a tank that is made up of only CFRP. The main challenge with a metallic structure is the heavy weight. Additionally the hydrogen embrittlement issue is also prevailing in most metals that leads to degradation of the tank [5]. The composite tanks overcome these challenges and provide lightweight construction but face limitations of their own like matrix microcracks [6, 7]. The latest type of pressure vessel is a Type V composite pressure vessel that offers a complete carbon fiber-reinforced polymer (CFRP) based tank structure. The Fig. 1 illustrates the five different kinds of pressure vessels.

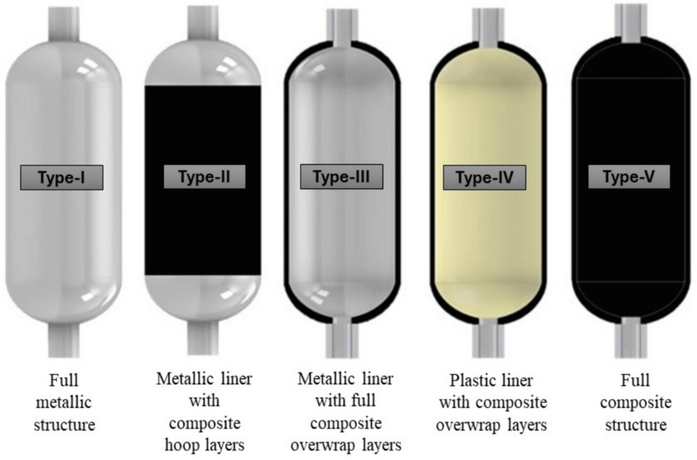

Fig. 1. Illustration of the various types of pressure vessels

Several researchers are working on the development of Type V tanks. Liner less tanks were fabricated in 1999 by Meyer et al. for cryogenic fluid storage in space applications [8]. Although there was no leakage or microcracks in the structure, the tank developed wrinkles due to collapse of the hollow sand mandrel. Similarly, Mallick et al. reported in 2004 about the development of a liner less tank for space application, focusing on crack resistant material development and failure analysis [9]. However, the application of Type V pressure vessels in automotive sector is quite limited in the available literature. Hassan et al. provide a detailed discussion on the various types of pressure vessels and elaborate on the research trends in the current scenario [10]. Air et al. report on the design and manufacturing of a Type V pressure vessel using the automated fiber placement technology [11, 12]. The tank had several leakage points and therefore held much lower hydrostatic pressure, but it laid foundation for the fabrication of a pressure vessel. This report highlights the significant challenges involved in developing a Type V pressure vessel for automotive applications.

2 Motivation

The DigiTain project aims to develop models for digital product development to demonstrate sustainable architecture [3]. One of the major components of this initiative is the development of a 700 bar hydrogen storage pressure vessel. The Type V pressure vessel is expected to have significant impact on the hydrogen economy by demonstrating lightweight design and high vehicle efficiency through very high strength to weight ratio. However, the development of a Type V pressure vessel poses several challenges [13]. Some of the significant challenges are (a) Hydrogen compatibility (b) Durability and fatigue resistance (c) Regulatory compliance (d) Cost effectiveness considering materials, manufacturing and system integration; especially for automotive applications (e) Gas permeation and (f) Manufacturing complexity. Gas permeation and manufacturing complexity are the major challenges and are discussed in details in this article.

2.1 Manufacturing Complexity

Introducing a liner less design increases the manufacturing complexity of the Type V tanks. Without the liner, the tank material itself must meet the requirements for strength, permeability and compatibility with hydrogen. In order to manufacture the tank structure, a mandrel is essential to provide shape and dimensions. A mandrel is a structure that serves as a core around which materials are wrapped to obtain composite structures at the end. The Type V tanks generally use removable mandrels to manufacture the tank [14–16]. These are made of sand or plaster or sometimes 3D printed materials. These mandrels are extensively developed for the purpose of removal post curing the tank. However, they face certain limitations. Firstly, it is difficult to remove the complete material post-curing especially with geometries that have smaller polar openings. Secondly, the sand based mandrels are manufactured based on the specific geometry of the tank. Therefore, they come with a high price, especially for research production. Even for later series production, the cost of the mandrel is a significant factor aiming at the automotive applications. Thirdly, the 3D printed resin material mostly has lower melting temperature than the curing temperature of the overwrap towpreg. Therefore, the mandrel disintegrates during the tank curing. Finally, another major challenge is the limitation to attach barrier film or coating for a removable mandrel. These limitations, listed above, pose research opportunities for the development of a new mandrel concept.

Therefore, a new integral mandrel technology has been introduced in this project that makes the mandrel out of CFRP and does not require removal from the tank. This mandrel is expected to act as a partial load bearing structure in the tank and reducing the total number of overwrap layers compared to a Type IV pressure vessel, demonstrating weight saving potential for the automotive sector. Additionally, it can be a cost-effective process since it is manufactured with a reusable metallic mold. Finally, as the mandrel eliminates the use of sand, plaster or removable materials, it can be a sustainable solution that encourages low wastage. Thereby, looking at these major advantages, the integral mandrel has been studied as an alternative technique for Type V tank development. This article discusses the initial investigations made in this direction. The detailed research and development of the mandrel is in the future scope of the research.

2.2 Gas Permeation

One of the primary concerns with a liner less Type V pressure vessels is the permeation of hydrogen outside of the tank owing to the lack of a polyamide-based liners as in the Type IV tanks [17–19]. This can lead to the loss of the stored amount of gas and also pose potential safety risks. Therefore, it is a crucial challenge for a Type V pressure vessel to ensure safe and efficient storage of hydrogen. Hydrogen is the smallest and lightest molecule and has the potential to permeate through various materials. Figure 2 illustrates the leak path formation and subsequent loss of fuel through the composite. The driving range of the vehicle depends largely on the amount and pressure of the hydrogen stored in the pressure vessels. Therefore, premature leaking and structural degradation need to be carefully avoided especially without a liner. The tank structure needs to make sure that hydrogen doesn't permeate out while sustaining high pressure and the environmental loads. Consequently, designing the pressure vessel with these criteria in mind is a crucial step in the development process.

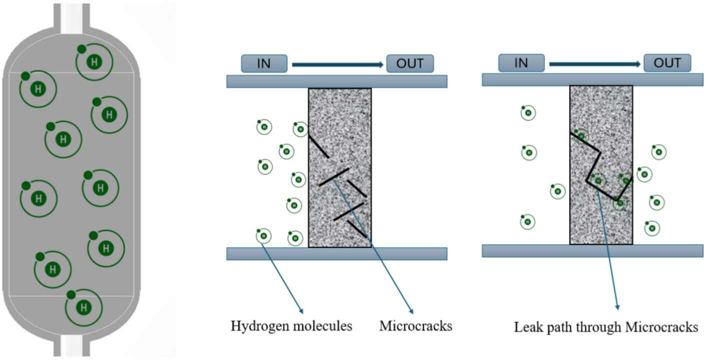

Fig. 2. Hydrogen molecules tend to leak out of the composite walls of the pressure vessels. The microcracks are developed owing to the cyclic loading and they tend to form leak paths through these microcracks that leads to gas leakage.

3 Preliminary Investigations and Results

3.1 Design of the Mandrel

The preliminary model was designed using µwind software by Mefex GmbH [16]. The model was developed considering the installation space and dimensions required within the framework of the DigiTain project. The laminate thickness was determined to be 8.55 mm. The inner diameter of the tank is 135 mm, and the cylinder length is 1050 mm as shown in Fig. 3. The modeling utilized towpreg material with T700 24K carbon fibers. The primary objective was to ensure the structure was free from fiber failure. Initial evaluations indicate that the design can withstand a burst pressure of 1400 bar without fiber failure, as depicted in Fig. 4. Further assessment will focus on Inter-fiber-failure as this of greater importance in Type V tank development considering the absence of the liner. Taking into account the current design setup the plan involves using the initial two hoop layers as the CFRP tube and attaching CFRP domes to it and beginning the overwrap from the third layer.

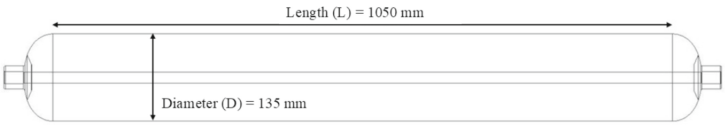

Fig. 3. Dimensions of the 1400 bar pressure vessel according to the design based on installation space.

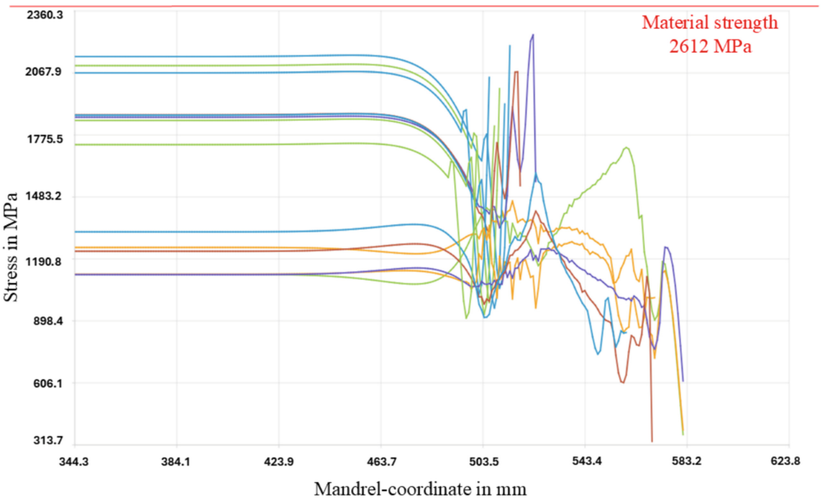

Fig. 4. Stress distribution along the tank geometry calculated by the analytical method using µwind software and the red line denotes the material strength from the datasheet.

3.2 Manufacturing Trials

The integral mandrel is divided into three different sections, one long tubular CFRP section and two dome caps. The metallic bosses are typically designed to match the external piping and valve connections. They are attached to the dome caps. The manufacturing steps for a mandrel development and subsequent tank manufacturing is shown in the Fig. 5.

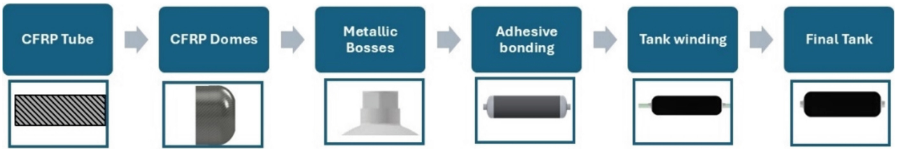

Fig. 5. The manufacturing flowchart for the development of a CFRP based mandrel. The dome caps and tube are adhesively bonded together with the boss and then filament winding is done on the structure which is then cured to obtain the complete tank structure.

CFRP Tube

The metallic tooling made of Aluminum alloy is used. This metallic tooling provides precision to the interior profile of the finished composite structure. The CFRP tube is obtained by winding towpreg on this metallic tooling. After curing, the thin composite tube is taken off the metallic tooling. The metallic tooling is made of AlMgSi0,5 with a roughness average (Ra) of 1 µm. The towpreg used here is made of 24k T700 towpreg by Kümpers [20]. The tube is manufactured using a robotic filament winding machine by Roth Composite Machinery GmbH [21].

CFRP Dome Caps

The dome caps are made up of thin composite parts using a 3D-printed tooling for preliminary investigations. The inner surface of the tooling is lined with silicone for easy removal of the composite part and to provide enhanced surface finish. The conventional and easily available twill weave (2 X 2) fibers and epoxy resin system are used for the initial investigations (Epikote RIMR 426 with hardener RIMH 435). They enable an ambient cure system and medium low viscosity. The twill weave fibers provide drapability, which is the ability to conform to different three-dimensional shapes, which helps to manufacture dome-shaped parts. The tooling is designed to provide full outer shape to the dome caps. Figure 6 shows the CAD design of the tooling and images of the actual tooling used for the manufacturing. The tooling is divided into two parts that are joined using screws and leads to easier removal of the composite part after curing.

A simple hand layup technique was applied for these initial investigations. Dry fibers were placed and the resin was applied using a brush; subsequently the hand roller was used to ensure uniform resin distribution and obtaining the required thickness. Figure 7 illustrates the process used for the dome fabrication. To avoid voids in the composite part, vacuum bagging was done above the mold during the curing process.

The initial investigations provide results that are essential for further validation. The CFRP tube is manufactured with precise geometry and surface finish owing to the metallic removable tooling. The process is sustainable due to the reusable metallic tooling. The technique is reproducible, as the geometry is repeatable. Figure 8 shows a sample CFRP tube manufactured by filament winding on metallic tooling.

Regarding the dome caps, initial results of the manufacturing trials suggest a few limitations. Firstly, the dome structure is technically complicated to manufacture using hand layup and therefore requires a significant labor-intensive approach. The use of a more advanced and simple technique is essential, such as RTM. Secondly, the slots for boss attachment required holes in the dome caps and it is difficult to manufacture a

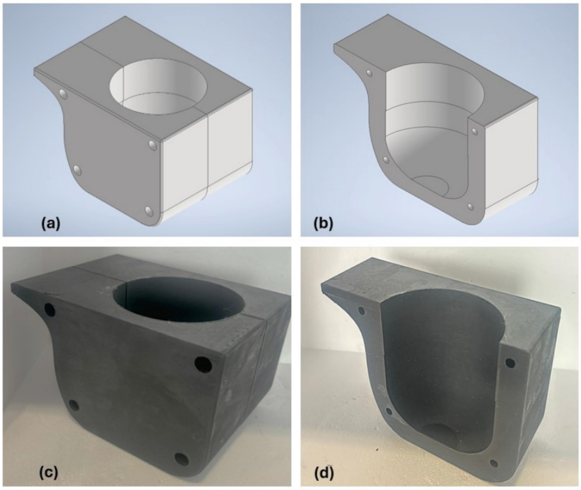

Fig. 6. CAD details of the tooling designed for the manufacturing of the dome caps. (a) shows the two portions of the tooling attached and (b) shows the inner surface of the tooling with slot for boss attachment and slit for tube attachment. (c) and (d) show the actual images of the tooling

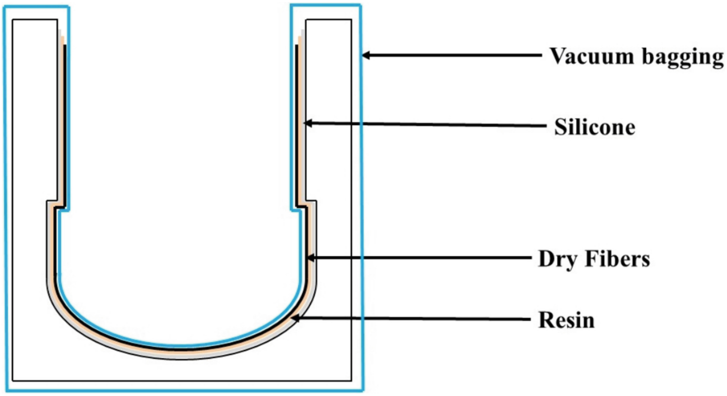

Fig. 7. Hand layup process for the dome caps manufacturing using the 3D printed tooling.

dome cap with hole using the currently utilized technique. Thirdly, the reproducibility of the composite part seems challenging since the hand layup technique offers lower precision in geometry. Figure 9(a) shows the images of the dome caps as manufactured. Figure 9(b) shows the assembly of CFRP dome caps and tube.

The preliminary trials for the integral CFRP mandrel have been completed. The tubular section of the mandrel is manufactured by winding and is therefore a promising solution. However, the dome caps are complicated composite parts and hence show limitations for reproducible and precise fabrication. The next step could involve using a different technique such as resin transfer molding (RTM) to produce the dome caps.

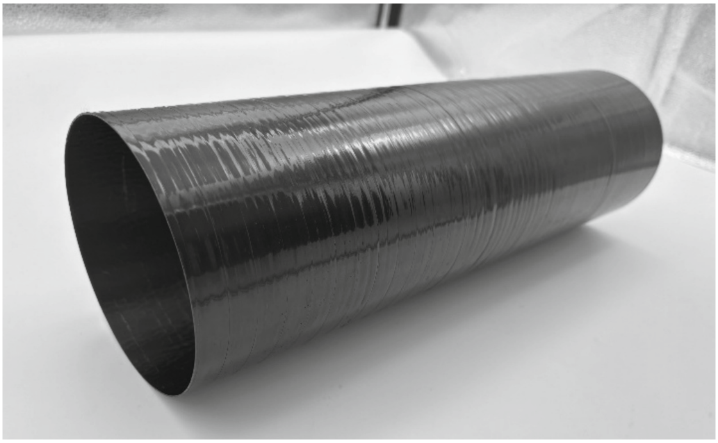

Fig. 8. CFRP Tube manufactured by winding towpreg on a metallic tooling.

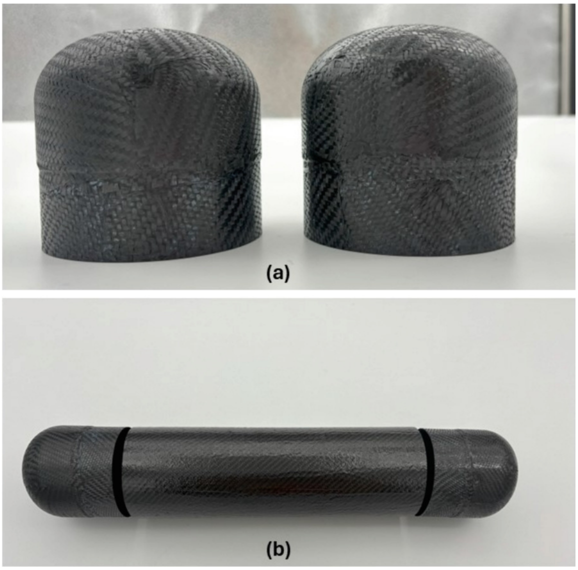

Fig. 9. Images of the fabricated CFRP integral mandrel components in the initial investigations (a) The image of the dome caps manufactured using hand layup technique. (b) CFRP tube fabricated using prepregs wound around a metallic tooling and the dome caps are attached on both ends to illustrate the CFRP based integral mandrel concept.

Furthermore, additive manufacturing also offers numerous advantages in this regard, especially for production of complicated designs like the dome caps. An improved step could be a 3D- printed dome cap structure integrated with a CFRP tube to produce the final mandrel. The 3D- printed part however needs to be high temperature resistant so that it doesn’t disintegrate during the curing of the final tank.

3.3 Gas Permeation Through the Tank Walls

The challenge of gas permeation is a significant factor for Type V pressure vessels in the absence of a liner. The integral mandrel is expected to provide structural stability for tank winding and also mitigate the hydrogen permeation through the tank walls. From the structural perspective, the fibers define the stress and strain limits of the full composite. Whereas the leakage component is defined by the matrix part of the composite. As explained in the Sect. 2.2, the composite is subjected to the operating pressure of the tank and tends to form microcracks. Additionally, the resin system needs to hold the laminates together to avoid delamination of the composite structure in the tank. Hence, it is essential that the resin system is toughened to be crack-resistant until the operating pressure of 700 bar [22, 23].

The gas permeation is analyzed at sample level using the in-house diffusion test set up as shown in the Fig. 10. This set up required samples to be within 1mm thickness and less than 50mm in dimensions and need to be fully dried for 48 h prior to the testing. The specimens are only subjected to a low pressure of 4 bar since the leakage through a sample is pressure dependent, but the material specific permeation property is not significantly affected by it. The test set up uses helium instead of hydrogen for the initial test on the samples. They both have similar molecular dimensions and helium is non-flammable, inert and non-reactive. Additionally, helium is not common in the environment allowing high detection accuracy.

Fig. 10. Schematic diagram showing the inhouse permeation test set up.

The mandrel is made up of CFRP components, and since the Type V is a liner less design, the mandrel itself should ensure that the tank is leak-tight. Therefore, it is essential to evaluate its permeation properties. The flat laminate sample of 0.8 mm thickness was fabricated using vacuum-assisted curing of four layers of twill (2 x 2) prepreg. The measurement was done for 24 h and against a pressure of 4 bar of helium on a specimen prepared using a sample twill CFRP prepreg as used for the dome cap manufacturing trials. The leak rate with respect to time in hours is plotted in the Fig. 11.

The permeation is a property of the material and it is evaluated from the experimentally obtained leak rate by using the Eq. 1.

$$P = \frac{Q \times d}{\Delta p \times A} \tag{1}$$

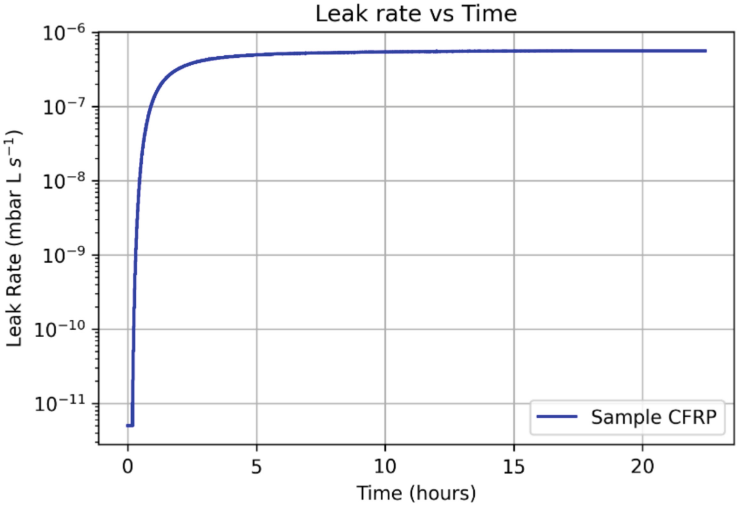

Fig. 11. The leak rate of the CFRP sample measured against time for a 24h duration.

In Eq. (1), P is the permeability, Q is the leak rate obtained through the experiments, d is the thickness of the sample, Δp is the pressure difference of the gas on both sides of the sample and A is the surface area of the sample that comes in contact with the gas [24]. The maximum permeability value obtained is 4.14 x 10^{-14} mm^2/s which is lower than that of liner samples due to the presence of fibers but is expected to worsen as microcracks develop in the resin [19].Gas leakage through composites has been an extensively analyzed topic, and various reasons can be identified. Firstly, diffusion is when the gas molecules seep through the resin system. Secondly, sorption can be another factor in which the gas molecules are attached to the surface and change the mechanical properties over time. This can lead to further gas permeation through the composite material. Thirdly, and the most vital cause can be the formation of microcracks. They are induced due to mechanical, thermal and environmental stresses and lead to formation of leak path [25]. Therefore, liner less tank structure requires significant reinforcement for a barrier layer. This barrier can be integrated into the composite either through modified resin or through layer of braided plies as shown in the patent by Cronin et al. [26]. In another aspect it can also be a thin coating material that can decrease the permeation of gas. Further steps for a leak tight tank using the integral mandrel can be integrating the barrier layer as foil in the CFRP structure at mandrel level. The overall summary is that extensive research is still needed for the development of a Type V tank with a leak tight structure.

4 Conclusion and Critical Discussion

Type V pressure vessels are a groundbreaking advancement in hydrogen storage technology. They differ from Type IV vessels by eliminating the internal polymer gas barrier. Instead, Type V vessels use carbon fiber laminate to provide the necessary structural properties and prevent gas leakage. Notably, Type V vessels have found utility in launch vehicles and spacecraft applications and are now emerging as a promising solution for achieving lightweight and efficient fuel storage in automotive applications owing to its high strength to weight ratio and increased capacity resulting due to absence of a liner. This article explains the various hurdles in the development of a Type V pressure vessel for automotive application. The discussion delves into two primary limitations: manufacturing complexity and gas permeation, offering detailed insights into each aspect.

This article proposes an integral mandrel concept in which a CFRP-based structure is used as a mandrel upon which filament winding can be done to obtain the full tank structure. This mandrel provides additional load-bearing capacity and hence the number of overwrap layers are expected to be reduced. Secondly, a CFRP based structure is expected to provide cost effectiveness as compared to sand or plaster based removable mandrels paving the way for low cost mass production. Finally, the integration of the mandrel structure into the tank design holds the potential for sustainability and reduced waste, as it streamlines manufacturing processes and material usage. The integral mandrel is anticipated to offer the aforementioned functional advantages and, as such, holds potential for integration into the automotive industry. The initial investigations have been conducted to assess the manufacturing process of the integral mandrel, with subsequent analysis aimed at predicting the permeation behavior of the tank. Permeability assessments revealed detectable leakage in the sample within 24 h, highlighting the necessity of incorporating a permeation barrier layer. In conclusion, addressing the challenges of high-pressure Type V hydrogen tanks is critical for advancing automotive applications, requiring innovations in materials, permeation control, and safety standards to support hydrogen's role in fossil-free transportation.

5 Future Scope

Anticipating future advancements, there is ample room for further development of the integral mandrel. While the tube structure has been successfully obtained, the dome cap structure presents a few manufacturing limitations. A potential next step could involve utilizing different techniques such as resin transfer molding for the dome caps manufacturing. Additionally, additive manufacturing could also be employed to obtain a 3D printed dome cap. Permeation studies on the composite mandrel indicate a need for enhanced barrier properties. One approach could involve modifying the resin to imbue it with inherent barrier characteristics. In that direction, nanomaterials that can block the leakage like Graphene can be added to the epoxy resin, followed by the permeation analysis at the sample level. Alternatively, integrating a thin barrier film into the mandrel's structure could ensure complete leak tightness. Metallic foils can offer full barrier against fuel leakage but their integration into a tubular tank wall structure will require extensive research and development efforts. In summary, advancing the integral mandrel through innovative manufacturing techniques and enhanced barrier properties is essential for overcoming current challenges and improving the performance of Type V hydrogen tanks.

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