Scalable Hydrogen Storage and Transport Systems

Stephen Johnston, Chris Kondogiani, Anthony Lancione
Noble Gas Systems
Novi, Michigan USA 48375
info@noblegassys.com / 1-248-607-0890

Abstract

Advances in conformable tank technology have resulted in opportunities to harness and deploy hydrogen energy in a variety of operational environments. Various use cases are described, and the benefits of these unique storage systems in vehicular, stationary, and bulk storage applications are illustrated. The impressive scalability of conformable hydrogen tank production is also explained, as it relates to the cost effective and broad application of these storage systems.

Keywords

Hydrogen; Containers; Conformable Tanks; Compressed Gas; Hydrogen Transport; Type 3; Type 4; HGV2; Bulk Storage

Introduction

As the demand for clean and sustainable energy sources continues to rise, scalable hydrogen storage and transport systems play a crucial role in facilitating the widespread adoption of hydrogen as an alternative fuel. This white paper aims to highlight the benefits of scalable systems for high-pressure hydrogen storage in transportation and usage, focusing on advantages to end-users and the production process.

Hydrogen Storage and Transport System Types

Traditional Storage Systems: Storage and transport of hydrogen has traditionally been accomplished in three ways: (1) compressed and/or cryogenic storage of liquid hydrogen (LH2), which is most applicable for the transport of large quantities of hydrogen, but within a limited timeframe; (2) compressed hydrogen gas (CH2), which involves the storage at high pressures, typically 250 – 700 bar in cylindrical containers made of metal (Type 1), hoop reinforced metal (Type 2), fully reinforced metal (Type 3), and fully reinforced plastic liners (Type 4); and (3) lower pressure, chemical storage such as in ammonia (NH_3) or with metal hydrides.

Conformable Tanks: Conformable tanks, a type of scalable system, offer increased storage capacity and design flexibility. They optimize space utilization within ships and vehicles and enable efficient integration without compromising safety or performance. These types of tanks were envisioned as a way to store high pressure gasses, beginning with patent 3,432,060 for a tubular pressure vessel, filed in 1965 by John James Crowley.[1]

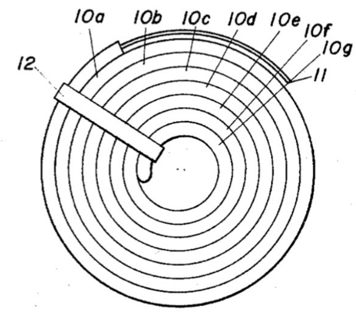

Figure 1. Image from J.J. Crowley patent.

More recently, with the advent of improved materials and manufacturing methods, these types of conformable tanks have been refined and developed to provide viable alternatives to more traditional methods. Additionally, existing regulatory standards, such as CSA / ANSI HGV2:2021 (HGV2)[2] have defined a pathway for certification for these tanks for use on hydrogen powered vehicles and transport systems. A few types of conformable tanks are addressed by this standard, as defined below:

Tank Arrays: Tank arrays consist of multiple smaller cylinders strategically arranged within a vehicle or storage system. This arrangement allows hydrogen to be stored in non-cylindrical shapes, which may be easier to package than a single large cylinder. The topology of these systems is similar to the racks used to deliver industrial gas cylinders in quantities like eight or 16.

Serpentine-Style Containers: Serpentine-style containers feature a multi-segment construction that maximizes the use of available space. These containers offer increased storage capacity without compromising vehicle design or performance. The serpentine configuration minimizes wasted space, improving the overall efficiency of the hydrogen storage system. These tanks are made up of multiple interconnected segments typically contained inside a protective shell. Segments of different lengths and quantity can be used to fill a given space, even if it is irregular. An additional benefit to these systems is the elimination of connections between the segments, which reduces potential leak paths and reduces the weight and complexity of the storage system.

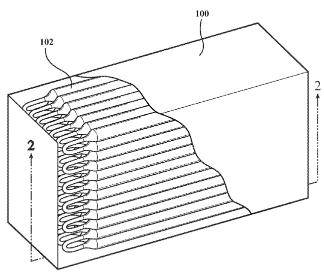

Figure 2. Image from Kondogiani and Donoughe patent 9,850,852 showing serpentine style conformable tank.[3]

Use Cases for Conformable Tanks

Because it is lighter, easier to produce, and contains more specific energy than batteries, hydrogen has many potential applications across a wide spectrum of applications. While the following list is not exhaustive, it does illustrate how conformable tanks can enhance these attributes.

Portable Applications: Conformable tanks enable the production of purpose-built, small, lightweight systems for portable applications. Because they can be made to fit inside existing containers, the convenience of storage and transport is enhanced. These systems can be used to power remote generators, either with internal combustion engines or silently operating fuel cells.

Because hydrogen is easy to produce from water using electrolysis, an entire remote production and storage facility for hydrogen can be deployed to eliminate the need for the transport of fuel to remote locations.

This system is also lighter weight and exhibits a shorter refilling time, leading to more uptime compared to the long recharge cycles of batteries.

Mobility Applications: Because of their ability to increase the storage capacity of hydrogen within irregular spaces, mobile platforms including ground vehicles, aerial systems, underwater vehicles, and aerospace applications benefit from the application of conformable tanks.

Using hydrogen in mobility applications can be superior to batteries because of the ability to store more onboard energy. In 2022, Lockheed Martin announced that it had successfully flown an unmanned drone over 39 hours using a hydrogen fuel cell,[4] which is a significant multiple of what is achievable using a battery powered counterpart. Larger vehicles, from cars to heavy duty trucks, airplanes, and cargo ships can all benefit from the ability to carry more energy and refuel faster.

In these cases, because compressed hydrogen takes up more space than liquid fuels, conformable tanks can be employed to minimize the additional space required.

Bulk Storage and Transport: As hydrogen applications begin to come online, it will be necessary to store and move large quantities of compressed hydrogen from sources of production to intermediate users and end customers.

Current systems of transport, such as cryogenic containers for liquified hydrogen, and pipelines will need to be supplemented by additional compressed gas storage to meet the needs of users across a diverse range of geographies and with a variety of demand profiles. The benefits of lightweight, space-efficient conformable tanks are ideal for those applications requiring large quantities of compressed hydrogen at maximum storage efficiency and flexibility to reduce the number of containers and shipments.

Benefits to End Users

Increased Storage Capacity: Scalable hydrogen storage and transport systems allow for higher hydrogen storage capacity compared to traditional cylinders. These systems can be customized and expanded to fit various vehicle designs, maximizing the use of available space, and enabling longer driving ranges. Compared to a single large cylindrical volume, the ability to take up more of the available space is enhanced using smaller, modular vessels or segments.

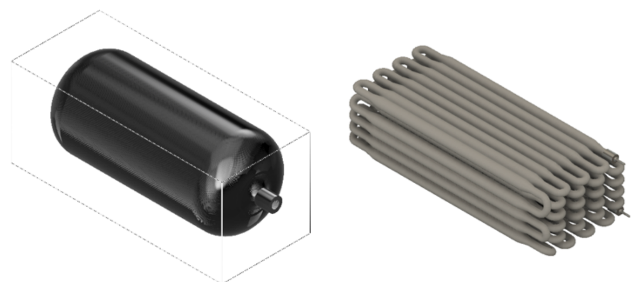

Figure 3. Conformable tank increasing storage within a rectangular volume.

Enhanced Safety: Scalable systems incorporate advanced safety features, such as integrated pressure relief systems and impact-resistant materials. These advancements minimize the risk of leakage or rupture, ensuring the safety of both end-users and hydrogen-powered vehicles. Additionally, the fact that the gas volume is separated into multiple segments, whether they be interconnected or not, provides a natural attenuation for the energy released by a tank failure.

Improved Efficiency: The lightweight construction of scalable systems reduces the overall weight of the storage system, leading to improved vehicle efficiency, extended driving range, and increased payload capacity. Additionally, the reduction in weight translates to lower energy consumption during transportation, making scalable systems more energy-efficient overall.

Design Flexibility: Scalable systems offer design flexibility, allowing for customization and integration into various vehicle types. These systems can be adapted to fit the available space without compromising vehicle functionality or aesthetics, reducing the cost of adapting existing platforms to enable the use of hydrogen fuel.

Scalable Production Process Benefits

Cost Efficiency: The manufacturing process of scalable hydrogen storage and transport systems offers cost advantages over traditional cylinders. A significant cost driver is associated with the tooling required to make each unique size of cylinder liner, and tooling cost grows with increasing cylinder size. For larger cylinders with lower expected production volumes, these costs are amortized over fewer units, making them even more costly to produce.

In contrast, using smaller, modular tanks reduces total tooling costs, and increases the production volume associated with any particular vessel size. In the case of serpentine-style conformable tanks, the length of each segment can also be varied, meaning that a single set of tools can produce an infinite number of tank designs. The tank design framework shifts from a discussion of smaller vs. larger tanks to less vs. more tank.

Tank Certification: Production designs must be certified to an applicable standard, such as HGV2, prior to full production. Design qualification tests must be repeated for tank designs that vary from each other (e.g. vessel length, diameter, reinforcement material, etc.) beyond a small operating window. However, using the same vessel construction to make repeated or conformable systems allows the same certification to apply to a wide variety of shapes and sizes. While some system tests, like the drop test, for example, may need to be repeated for each tank design, most of the vessel-specific tests still apply. Because tank certification is a costly and time-consuming process, this feature can significantly reduce the cost and the time to market for implementing new designs.

Production Efficiency: Scalable systems can be manufactured using automated processes, resulting in increased production efficiency and reduced labor costs. The flexibility in design and production processes facilitates seamless integration into assembly lines, streamlining production and enhancing overall manufacturing productivity.

Distributed Manufacturing: The low cost of production equipment enables multiple smaller production sites that are located near customers and demand centers. This reduces the burden of supply chain costs and logistics, improving responsiveness to customers.

Economic Benefits

Materials Supply: As with many lightweight components, particularly in aerospace and high-performance automotive applications, the reinforcement of Type 3 and 4 tanks are typically constructed with carbon fiber. As the demand for these tanks increases, tank manufacturers will become significant consumers of this difficult to produce material, which will increase costs, and result in significant capital expenditures to increase capacity. Conformable tanks can be produced with a wider variety of materials, many of which do not compete with the construction of lightweight components in other industries.

Recyclability and Circularity: Because the fiber used in the construction of composite reinforced tanks is embedded in epoxy, it is not easily reused or recycled. As a result, much of the tank ends up in a land fill at the end of its life. Alternative construction, such as dry fiber application used in some conformable tanks enables the different materials to be separated. So, these types of tanks enable recycling and reuse of the constituent components, resulting in a significantly higher circularity index, and a lower waste footprint.

Production Scale: The future demand for hydrogen storage tanks is significant, particularly when automotive and aviation applications are forecasted to rise significantly in the late 2020’s and early 2030’s. Meanwhile, the lack of significant infrastructure, high cost of hydrogen production, and limited number of applications means the current market is small. This means that current tank prices are a burden to the adoption and growth of early adopters. By the nature of the production of conformable tanks, the same equipment can be used to produce a wide variety of tanks at a reasonable cost. As a result, many small markets can be served economically, as demand growth increases.

Just as the production methods and modularity of these systems enable economic production at low part volumes, they also enable small and large capacity systems to be produced at proportional costs. As described above, the cost of tooling and equipment for large tanks is disproportionately high, which causes them to be relatively more expensive. However, making large containers from many small containers, especially conformable tanks, means that the cost of the system varies more linearly with the capacity.

Transitional Infrastructure: Compared with liquid fuels, current hydrogen infrastructure is limited. Although significant public funding is beginning to emerge, building the vast gas storage and transportation networks required to enable widespread hydrogen usage will be costly and slow. Alternatively, using intermodal storage containers to move hydrogen from production to fueling sites, through existing networks of shipping, rail, and trucking, can happen relatively quickly and with require much less investment.

While hydrogen production and demand centers are developing, it may be difficult to predict the most advantageous locations. The risk of wasted infrastructure investment means that sites and pipelines must be carefully studied and planned. Alternatively, mobile storage containers for compressed hydrogen gas, enable fueling sites to be quickly built and operationalized. If the chosen site turns out to not be an ideal location, the facility can just as easily be moved to one of higher value.

This same mechanism can be used to serve temporary, remote, underserved, or peak demand locations that could not otherwise justify the establishment of permanent infrastructure. The ability to easily and cost effectively adjust the size, working pressure, and shape of the containers also makes it possible to optimize the development of ideal hydrogen storage and delivery mechanisms.

Conclusion

Scalable hydrogen storage and transport systems offer a wide range of benefits for high-pressure hydrogen storage, transportation, and usage. From increased storage capacity and enhanced safety to improved efficiency and design flexibility, these systems provide significant advantages to end-users. The production process also benefits from cost efficiency, scalability, and production efficiency. By considering various scalable system types, such as conformable tanks, tank arrays, and serpentine-style containers, the hydrogen industry can revolutionize storage and transportation, accelerating the adoption of hydrogen as a clean and sustainable energy source in various sectors.

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