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Liquid Hydrogen Storage and Supply Systems for Commercial Vehicles: Technologies, Standards, and Global Progress

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ABSTRACT

Liquid hydrogen offers compelling advantages for heavy-duty commercial transportation, including high storage density, rapid refueling, and high-purity hydrogen supply, making it more cost-effective than high-pressure gaseous hydrogen for long-haul applications. This paper systematically reviews the global development of liquid hydrogen-fueled commercial vehicles, highlighting key performance indicators from representative models: General Motors' "Hydrogen-3" (400 km range, 90 kg storage system), Mercedes-Benz's GenH2 heavy-duty truck (1000 km range, 80 kg storage system), and China's BAIC Foton 49-ton tractor (1000 km range, 110 kg storage system). The technical progress in core components is detailed, including onboard liquid hydrogen tanks (whose daily evaporation rates have been optimized from 2%/day to ≤ 6%/day), vaporized hydrogen supply, refueling technology, and exhaust systems. Furthermore, this paper summarizes domestic and international industry standards and identifies the most critical challenges for large-scale commercialization. These priorities include the lightweight and insulation optimization of onboard tanks, the domestic production of key refueling components (e.g., liquid hydrogen pumps and nozzles), and the safety control of liquid hydrogen sloshing under harsh driving conditions. The results provide explicit technical guidance for the promotion of liquid hydrogen commercial vehicles in China.

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1. Introduction

As a crucial component of future clean energy systems, onboard hydrogen storage technology is a pivotal factor limiting the large-scale deployment of fuel cell vehicles. Current review literature predominantly focuses on general onboard storage methods, such as 70 MPa high-pressure gaseous storage or solid-state metal hydride materials. A systematic, full-chain review specifically dedicated to the liquid hydrogen pathway—particularly its "storage, supply, refueling, and exhaust" systems for commercial vehicles—remains noticeably lacking [1-5]. Liquid hydrogen offers unique advantages, including high storage density, low storage pressure, low transportation costs, rapid refueling speed, and high vaporization purity, demonstrating significantly superior cost-effectiveness over high-pressure gaseous hydrogen for large-scale, long-distance commercial transportation applications [6-19]. Consequently, major global commercial vehicle manufacturers are intensively developing liquid hydrogen-fueled heavy-duty vehicles, with companies like BMW even achieving mass-production readiness. In contrast, related research in China remains nascent, with few reports of commercially available liquid hydrogen-powered commercial vehicles entering production [20]. Notably, the period between 2022 and 2023 marks a dense breakthrough phase for liquid hydrogen heavy-duty truck technology worldwide. Landmark prototypes or products were successively unveiled in China, Germany, and Japan, signaling the technology's formal transition from early exploration to the eve of commercialization. Despite this progress, there is still a lack of focused, systematic comparisons regarding the development status and critical system technologies (e.g., onboard liquid hydrogen tanks, vaporized hydrogen supply systems, refueling systems, and exhaust systems) for these vehicles. Therefore, this paper systematically focuses on commercial vehicles, comprehensively reviews and compares the application history of global liquid hydrogen fuel commercial vehicles and the current status of key technologies in the four core modules of storage and supply systems, and integrates the current industry standard systems for domestic and foreign civilian liquid hydrogen commercial vehicles. By identifying the most pressing technical challenges faced in the commercialization process of liquid hydrogen fuel vehicles and anticipating their future development trends, this paper aims to provide a clear framework guidance for the research, development, and promotion of liquid hydrogen fuel commercial vehicles in China, a timely and crucial field.

2. Commercial Applications

The development status of liquid hydrogen fuel commercial vehicles by major global automakers is shown in Table **1**. As indicated in the table, as early as the 1960s, the United States began developing commercial vehicles powered by liquid hydrogen, leveraging its experience in liquid hydrogen applications within the aerospace and military sectors. General Motors [21] developed the “FCEV Electrovan” truck in 1966, achieving a range of 193 km and a top speed of 113 km/h. Seven years later, they introduced the Chevrolet Montero truck powered by liquid hydrogen. Subsequently, countries such as Japan and Germany also initiated research into liquid hydrogen-fueled commercial vehicles. In 1976, Japan developed the Musashi II pickup truck prototype with a range of 650 km, followed by testing of the Musashi III-VI liquid hydrogen vehicles. In 2000, General Motors' Hydrogen One liquid hydrogen vehicle achieved a range of 400 km and a top speed of 140 km/h, with the entire hydrogen storage system weighing 95 kg [22]. Three years later, the Hydrogen One III [23], developed based on this model, further reduced the hydrogen storage system weight to 90 kg and increased the top speed to 150 km/h. The vehicle structure is shown in Fig. (**1**). In 2006, the hydrogen-powered BMW i7 series liquid hydrogen vehicle developed by Germany's BMW AG first met mass-production standards, achieving small-scale production and global exhibitions. In 2022, Tsinghua University, Beijing Foton Motor Co., Ltd., and the Beijing Aerospace Testing Technology Research Institute collaborated to develop the world's first liquid hydrogen heavy-duty truck. The prototypes—35-ton and 49-ton models—achieved ranges of 700 km and 1000 km respectively, with hydrogen storage system weights of 60 kg and 110 kg. This marked exploratory research for China's liquid hydrogen commercial vehicle sector [24]. That same year, Germany's Mercedes-Benz also developed the GenH2 liquid hydrogen heavy-duty truck, achieving a range of 1,000 km with a hydrogen storage system weighing only 80 kg. In 2023, China's Changzheng Automobile Corporation collaborated with Weishi Energy to launch the “New Changzheng 1 Liquid Hydrogen Heavy Truck” equipped with the “Jupiter” onboard liquid hydrogen storage system. This vehicle employs onboard liquid hydrogen supercritical pressure storage and supply technology, achieving comprehensive performance at a high international level. Additionally, Toyota Motor Corporation unveiled the world's first liquid hydrogen fuel cell race car, the GR Corolla H2, equipped with four liquid hydrogen fuel tanks. This vehicle successfully completed endurance testing at the Fuji 24-Hour Race.

Table 1: Development status of liquid hydrogen-fueled commercial vehicles.

Time (Year)	State	Model	Category	Purpose	Range (km)	Hydrogen Storage System Weight (kg)	Maximum Speed (km/h)
1966	United States	General Motors "FCEV Electrovan" [21]	truck	develop	193	/	113
1973	United States	Chevrolet Monte Carlo	automobile	develop	/	/	/
1976	Japan	Musashi 2	pick-up truck	test vehicle	650	/	/
/	Japan	Musashi 3-6	automobile	test vehicle	/	/	/
/	United States	Ford F250	pick-up truck	develop	/	/	/
2000	United States	General Motors "Hydrogen-1" [22]	automobile	develop	400	95	140
2003	United States	General Motors "Hydrogen-3" [23]	automobile	develop	400	90	150
2006	Germany	BMW745hL	automobile	suitable for mass production	/	165	230
2006	Germany	BMW760Li	automobile	suitable for mass production	700	/	290
2022	China	BAIC Foton 35t class lorry [24]	heavy-duty truck	test vehicle	700	60	80
2022	China	BAIC Foton 49t class lorry [24]	heavy-duty truck	test vehicle	1000	110	90
2022	Germany	Mercedes-Benz GenH2	heavy-duty truck	develop	1000	80	/
2023	China	Changzheng Company "New Long March 1"	heavy-duty truck	test vehicle	1000	80	/
2023	Japan	Toyota GR Corolla H2	racing car	test vehicle	/	/	/

Figure 1: General Motors "Hydrogen-3" Liquid hydrogen fuel cell vehicle.

3. Liquid Hydrogen Fuel Supply Process

The liquid hydrogen fuel vehicle storage and supply system primarily consists of five major modules: onboard liquid hydrogen cylinders, hydrogen dispensing nozzles, vaporization and pressure regulation systems, control modules, and safety venting systems, as shown in Fig. (**2**). The specific operational process is as follows: Liquid hydrogen is dispensed from the refueling station into the onboard cylinders via dispensing nozzles and related equipment. Once filled to the required level, the stable hydrogen supply system vaporizes the liquid hydrogen within the cylinders and delivers it to the fuel cell system. Considering that liquid hydrogen continuously vaporizes and increases in pressure due to heat leakage—particularly prone to pressure buildup during vehicle parking—the onboard hydrogen supply system is typically equipped with a safety monitoring, early warning, and response system.

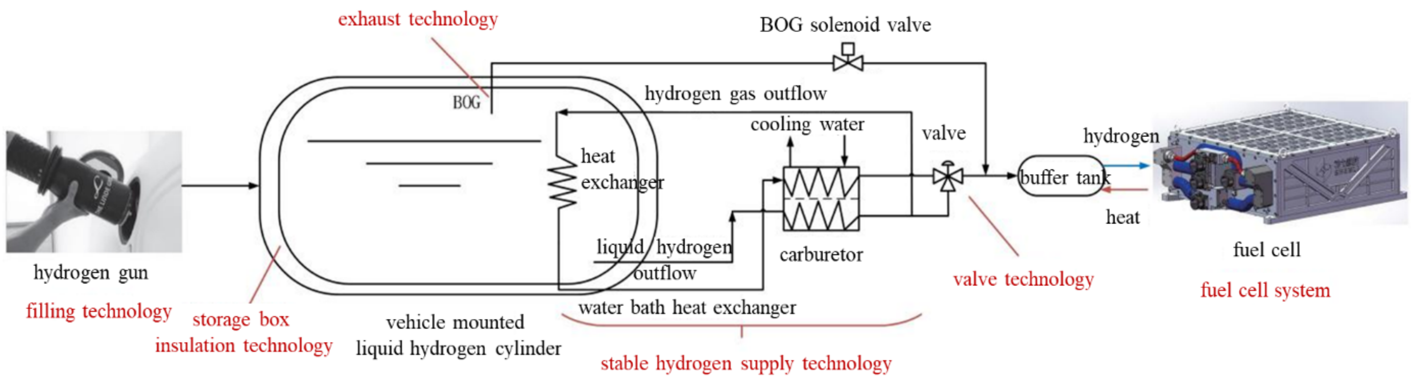


Figure 2: Schematic diagram of liquid hydrogen fuel supply process.

4. Key Technologies for Liquid Hydrogen Storage and Supply Systems

4.1. Development of Vehicle-Mounted Liquid Hydrogen Cylinders

Compared to high-pressure hydrogen cylinders, cryogenic liquid hydrogen tanks offer advantages such as greater hydrogen storage capacity and higher storage density. In terms of design, vehicle-mounted liquid hydrogen tanks serve as the core component of liquid hydrogen fuel commercial vehicles, typically adopting horizontal or cylindrical configurations [25]. They feature a double-walled structure with high-vacuum multi-layer insulation between the walls [26].

The current global development status of vehicle-mounted liquid hydrogen tanks is summarized in Table **2**. As early as the 1960s, Germany's Linde Company developed the LSH-150 [27] liquid hydrogen tank, measuring 1.47 meters in length, 0.51 meters in outer diameter, and possessing an effective volume of 150 L, with a daily evaporation rate reaching 2%/day. Eight years later, the American company MVE developed the LVH-150 liquid hydrogen tank with a maximum working pressure of 0.207 MPa and an effective volume of 189 L, achieving a daily evaporation rate of only 1%/day. In 1976, within the German DFVLR project, researchers developed the Type I liquid hydrogen tank, weighing 88 kg with a maximum working pressure of 0.8 MPa and an effective volume of 120 L, exhibiting a daily evaporation rate of 9%/day. Based on this, the Type II liquid hydrogen tank was designed, reducing its weight to 60 kg. with a maximum working pressure of 0.8 MPa and an effective volume of 120 L, exhibiting a daily evaporation rate of 9%/day. Building upon this, they designed the Type II cryogenic tank, reducing its weight to 43 kg while increasing the effective volume to 150 L and lowering the daily evaporation rate to 5%/day. During the early 1980s LASL trials in the United States, researchers similarly developed two liquid hydrogen cylinder models weighing 91.8 kg and 167 kg respectively, with effective volumes of 110 L and 155 L, and daily evaporation rates of 10%/day and 4%/day. Subsequently, BMW of Germany developed a liquid hydrogen tank with a 130 L capacity and 70 kg weight, achieving an evaporation rate as low as 2%/day [30]. In 2000, General Motors introduced the “Opel” liquid hydrogen tank, weighing 95 kg with an effective volume of 75 L and an evaporation rate between 1–3%/day. Three years later, the company introduced the “Hydrogen-3” tank with a volumetric hydrogen storage density of 36.6 kg/m^3. In 2003, supported by China's National 863 Program, a liquid hydrogen tank with an effective volume of 70 L and maximum working pressure of 0.4 MPa was developed, exhibiting a daily evaporation rate of 8.36%/day [32]. In 2022, China's Foton Motor Corporation collaborated with the Beijing Aerospace Testing Institute and others to develop vehicle-mounted liquid hydrogen tanks suitable for 35-ton cargo trucks and 49-ton tractor-trailers. These tanks weigh 30 kg and 80 kg respectively, operate at a maximum working pressure of 1.6 MPa, and exhibit a daily evaporation rate below 6% per day [24]. Fig. (**3**) [33] and Fig. (**4**) [34] show structural diagrams and physical images of selected vehicle-mounted liquid hydrogen cylinders.

Table 2: Development status of vehicle-mounted liquid hydrogen cylinders.

Time (Year)	State	Company/Project/ Experiment/Model	Dimensions	Maximum Working Pressure (MPa)	Daily Evaporation Rate (/day)	Effective Volume (L)
1966	Germany	Linde Company LSH-150 [27]	Length: 1.47 m, Outer diameter: 0.51 m	/	2%	150
1974	United States	MVE Company LVH-150 [27]	Weight: 42.6 kg, Inner diameter: 0.711 m	0.207	1%	189
1976	Germany	DFVLR project – tank I [27]	Weight: 88 kg, Diameter: 0.9 m, Height: 0.42 m	0.8	9%	120
1976	Germany	DFVLR project – tank II [27]	Weight: 43 kg	0.8	5%	150
1976	Japan	Musashi Institute of Technology [28]	/	/	2.5%	210
Early 1980s	United States	LASLTest-1 Liquid Hydrogen Cylinder	Length: 0.66 m, Outer diameter: 0.9 m, Total weight: 91.8 kg, Volume efficiency: 0.35%	0.448	10%	110
Early 1980s	United States	LASLTest-2 Liquid Hydrogen Cylinder	Length: 1.22 m, Outer diameter: 0.712 m, Total weight: 167 kg, Volume efficiency: 0.42%	0.448	4%	155
1988	Germany	BMW735i [29]	/	/	/	120
/	Germany	BMW745 [30]i	Weight: 70 kg	/	2%	130
1997	Germany	Meissner Company and BMW Company [31]	Length: 5 m, Diameter: 0.42 m	0.5	/	350
2000	United States	General Motors "Opel" Liquid Hydrogen Tank	Weight: 95 kg	/	1~3%	75
2003	United States	General Motors “Hydrogen-3”	Length: 1 m, Diameter: 0.4 m, Weight Hydrogen storage density: 5.1%, Volume hydrogen storage density: 36.6 kg/m³	/	/	/
2003	China	National "863 Program" Liquid Hydrogen Tank [32]	Inner container diameter: 0.35 m, Outer container diameter: 0.506 m	0.4	8.36%	70
2022	China	BAIC Foton 35t Truck Prototype Development [24]	Weight: 30 kg	1.6	≤6%	443
2022	China	BAIC Foton 49t Tractor Prototype Development [24]	Weight: 80 kg	1.6	≤6%	1109

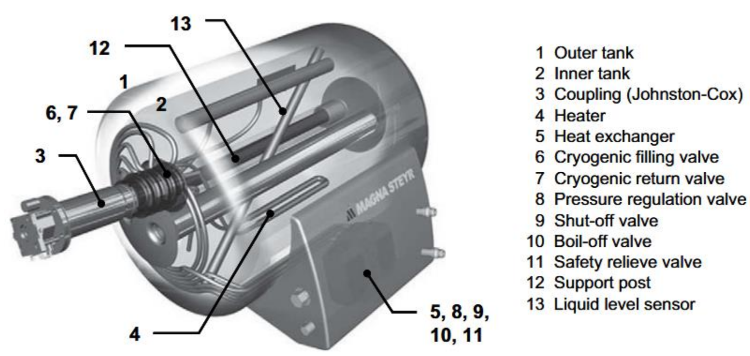
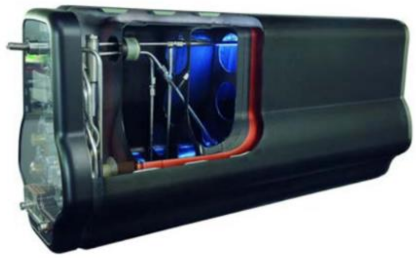


Figure 3: BMW onboard liquid hydrogen tank system [33].

In summary, although researchers have conducted extensive development, research, and design efforts on onboard liquid hydrogen tanks for commercial vehicles fueled by liquid hydrogen, numerous technical challenges remain to be overcome during the development process. First, to ensure operational safety, the material selection for liquid hydrogen tanks must not only mitigate hydrogen embrittlement effects but also maintain design strength requirements at cryogenic temperatures while exhibiting superior toughness and stability. This imposes



(**a**) BMW vehicle-mounted liquid hydrogen cylinder

(**b**) Linde vehicle-mounted liquid hydrogen cylinder

(**c**) Air liquid, liquid hydrogen cylinder

Figure 4: Actual image of vehicle-mounted liquid hydrogen cylinder [34].

stringent demands on the material's hydrogen embrittlement characteristics, adaptability, thermophysical properties, and mechanical performance [37]. Currently, liquid hydrogen tanks typically employ materials with excellent cryogenic mechanical properties, such as 316 or 304 austenitic stainless steel, aluminum alloys, or titanium alloys [35] for the inner liner. Among these, austenitic stainless steel offers superior toughness, plasticity, stability, hydrogen embrittlement resistance, and impact resistance at liquid hydrogen temperatures, making it the most widely used material for liquid hydrogen tanks. Aluminum alloys also exhibit high impact toughness, high specific strength, good machinability, and low hydrogen embrittlement sensitivity at cryogenic temperatures, making them an ideal cryogenic material. Titanium alloys offer high specific strength, excellent corrosion resistance, low thermal conductivity, and minimal thermal expansion coefficient [38], finding extensive application in aerospace. However, their elongation, impact toughness, and fracture toughness decrease with decreasing temperature, limiting their low-temperature use [39]. Simultaneously, carbon fiber composites can be wound around the inner liner to prevent material failures such as cracking or deformation. For the outer shell of liquid hydrogen tanks, materials like austenitic stainless steel or aluminum alloys can be selected to ensure the shell remains stable [36]. Furthermore, significant challenges remain in understanding the mechanisms governing cryogenic hydrogen tank materials. For instance, the relationship between material composition and brittle-to-ductile transition temperatures remains unclear, and data on low-temperature mechanical properties in the liquid hydrogen temperature range is scarce [40, 41]. Future research will inevitably focus on enhancing low-temperature mechanical performance, reducing production costs, and minimizing tank mass [42-44].

Second, to minimize evaporation losses and mitigate safety risks from rising internal pressure—particularly during long-term storage and transport—thermal insulation technology for cryogenic liquid hydrogen cylinders represents a critical priority [45, 46]. Enhancing insulation performance not only improves storage efficiency, reduces energy waste and economic costs, but also slows pressure buildup, thereby alleviating the burden on safety systems [47].

The Mills research team [48] employed an engineering process involving concept selection, manufacturing, and test validation to successfully develop a prototype liquid hydrogen tank suitable for high-altitude, long-endurance unmanned aerial vehicles (UAVs). This prototype was applied to the Phantom Eye aircraft program. The study emphasized the importance of balancing mass, thermal insulation, cost, and maturity. The tank employed spray-on foam insulation (SOFI) technology, utilizing either open-cell or closed-cell rigid polyurethane foam. This insulation features numerous microscopic pores, offering low density, high technical maturity, and seamless application. However, its thick insulation layer occupies significant space, and thermal expansion mismatch between the foam and metal walls may cause cracking. Fig. (**5**) and (**6**) present the design 3D rendering and physical prototype.

Sullivan [49] conducted a comparative study on various insulation methods for liquid hydrogen cylinders using numerical simulation techniques: ① Vacuum jacket combined with multi-layer insulation (MLI); ② Vacuum jacket without MLI; ③ Single-wall liquid hydrogen cylinder with sprayed foam insulation (SOFI); ④ Single-wall liquid hydrogen cylinder combined with high-density, high-strength aerogel; ⑤ Single-wall liquid hydrogen cylinder combined with low-strength aerogel. Results indicate that the vacuum jacket combined with MLI design significantly outperforms aerogel insulation methods.

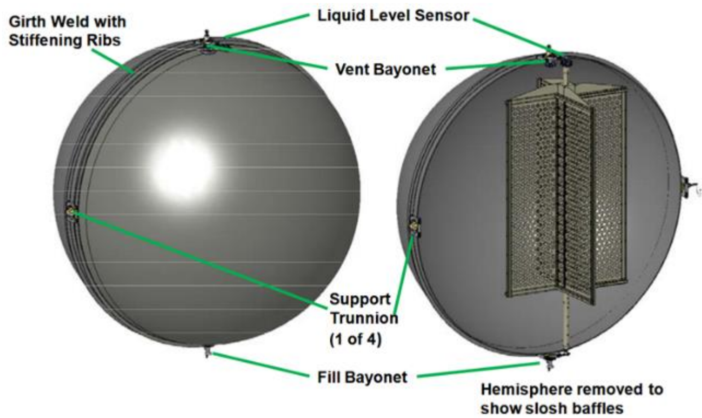
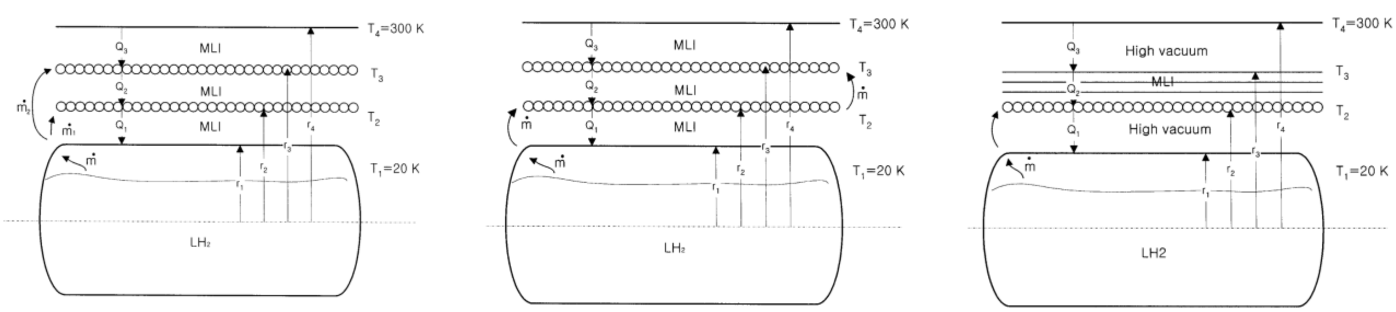


Figure 5: Spherical liquid hydrogen storage tank.

Figure 6: Actual image of a liquid hydrogen spherical tank utilizing. SOFI adiabatic technology.

The combination of high-vacuum MLI and a vapor-cooled radiation shield (VCS) is considered the optimal configuration for minimizing heat leakage from liquid hydrogen cylinders [50]. Kim's team [51] employed numerical analysis to evaluate three composite insulation configurations: ① fully filled MLI with parallel double vapor-cooled radiation shields (DVCS); ② Fully filled MLI with series-connected DVCS; ③ Partially filled MLI with single vapor-cooled radiation shield (SVCS). Results indicate that series-connected DVCS outperforms parallel-connected DVCS, while the third configuration exhibits performance comparable to fully filled MLI with DVCS. The Fig. (**7**) below illustrates the structural diagrams of the three insulation combinations.



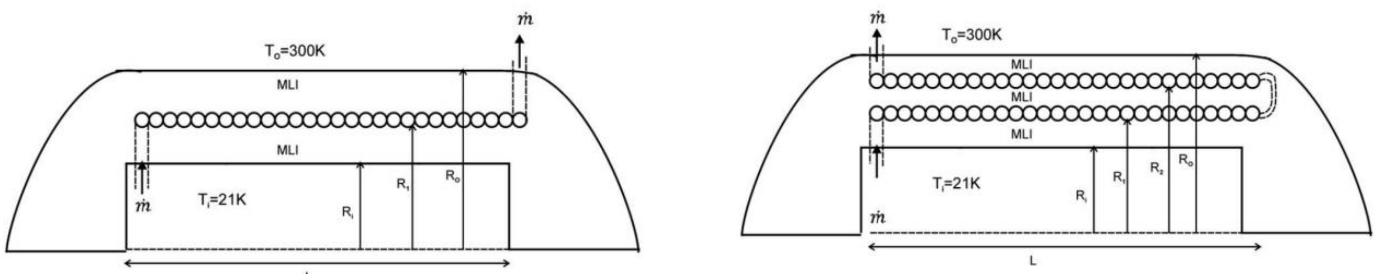
(**a**) Combined insulation of fully filled MLI and parallel-type DVCS

(**b**) Combined insulation of fully filled MLI and series-type DVCS

(**c**) Combined insulation of partially filled MLI and SVCS [51]

Figure 7: Structural comparison of three combined insulation configurations utilizing MLI and vapor-cooled shields (VCS).

Babac [52] employed numerical simulation methods to establish a two-dimensional numerical model, investigating liquid hydrogen cylinders combining MLI with both SVCS and DVCS. This study determined the optimal VCS position for minimizing heat leakage under both insulation methods. The study indicates that the thermal leakage rate of SVCS correlates with its radial position, achieving a 60% reduction in heat loss. For the DVCS insulation method, the thermal leakage rate can be reduced by 59%. The combination of SVCS with MLI appears to be the preferred insulation option. Fig. (**8**) shows the structural diagrams for both insulation methods.



(**a**) Single VCS+MLI structure (**b**) Dual VCS+MLI structure [52]

Figure 8: Combined structure of VCS+MLI with different layers.

The aforementioned scholars have focused on reducing heat leakage from liquid hydrogen cylinders through thermal insulation methods. In contrast, Xu's research team [50] explored structural optimization. Xu et al. employed a combined experimental and numerical simulation approach to optimize the thermal insulation support structure for a 0.9-meter diameter spherical liquid hydrogen cylinder. The novel insulation support, characterized by its point-contact structural design, reduced heat leakage through the support structure by at least 85%. Fig. (**9**) and (**10**) show the corresponding design schematic of the liquid hydrogen tank and the thermal insulation support structure, respectively.

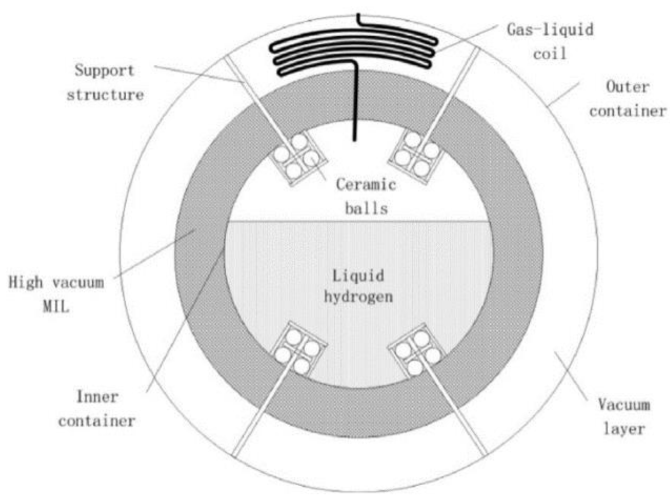


Figure 9: New insulated support structure for spherical liquid hydrogen cylinder [50].

Li Hang et al. from Tsinghua University [24] , in collaboration with the Beijing Aerospace Testing Technology Research Institute and Beijing Foton Motor Co., Ltd., addressed core technical challenges in the thermal insulation design, vacuum design, support structure design, and lightweight design of liquid hydrogen tanks for heavy-duty commercial vehicles. They employed a low-heat-loss support structure and an optimized MLI structure with a vacuum jacket featuring small spacing to develop a horizontal liquid hydrogen tank. This led to the successful development of the world's first distributed-drive liquid hydrogen fuel cell heavy-duty commercial vehicle. Fig. (**11**) shows the structural diagram of the onboard cryogenic horizontal liquid hydrogen tank for heavy-duty trucks proposed by the Beijing Aerospace Testing Technology Research Institute [53].

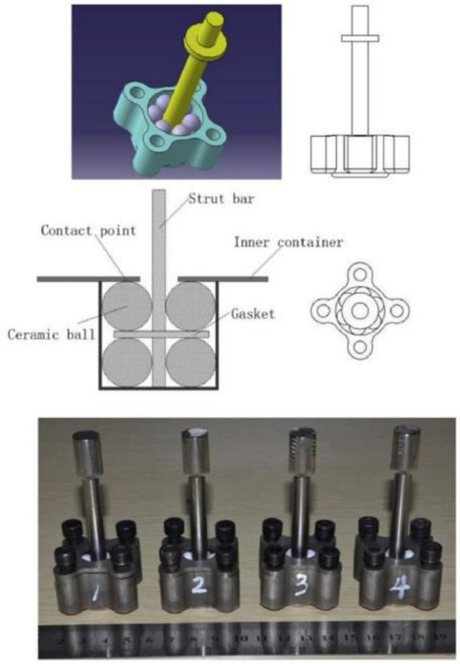


Figure 10: Schematic Diagram and Actual Image of the New Thermal Insulation Support Structure [50]

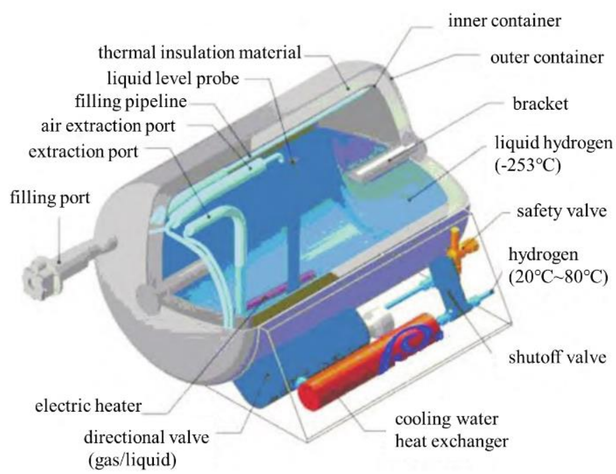


Figure 11: Structure diagram of vehicle-mounted liquid hydrogen cylinder [53].

Based on the above, thermal insulation optimization for vehicle-mounted liquid hydrogen cylinders can be approached from multiple angles: selecting insulation materials, employing insulation methods (combining vacuum jackets with multi-layer insulation materials and applying SOFI externally), and refining the cylinder's internal structure to minimize heat leakage. These measures will further reduce heat loss from the cylinders and extend the undamaged storage time of vehicle-mounted liquid hydrogen cylinders.

4.2. Liquid Hydrogen Cylinder Refilling Technology

Liquid hydrogen cylinder refueling technology constitutes a critical component of the storage and supply system for liquid hydrogen fuel vehicles. When a liquid hydrogen fuel vehicle runs low on liquid hydrogen energy, it must visit a hydrogen refueling station to replenish its onboard liquid hydrogen fuel [54, 55]. The typical refueling/re-refueling process from the hydrogen station to the vehicle's liquid hydrogen cylinder using existing technology involves the following steps: Controlled by a station button, helium flushes the coupling to cleanse the enclosed cavity created by the connection; a locking mechanism establishes a gas-tight seal between the vehicle's tank and the station; ball valves on both sides open simultaneously; the station-side cold finger of the coupling pneumatically extends into the vehicle side, ensuring proper cryogenic connection; Liquid hydrogen is pumped from the station's liquid hydrogen pump to the vehicle's tank via the dispensing nozzle; evaporated hydrogen is vented back into the station's high-pressure hydrogen storage cylinders; when the vehicle tank is full, a “tank full” signal from the vehicle automatically halts the refueling process; the cold finger retracts, ball valves close, and the locking mechanism disengages; the coupling returns to its support bracket [56-58].

Since the 1970s, Japan and Germany pioneered research into liquid hydrogen refueling technology, encompassing refueling processes, hydrogen dispensers, and refueling nozzles. As early as 1986, BMW conducted experiments using liquid hydrogen fuel in its BMW 745i model [59]. In 1999, a German-built liquid hydrogen refueling station achieved full refueling of a 120 L liquid hydrogen tank within 1.5 minutes. This refueling system and liquid hydrogen vehicle underwent demonstration applications at Munich Airport, marking the world's first public refueling station for liquid hydrogen-powered passenger vehicles. It supported both fully automated and manual refueling modes [60]. Domestically, although development began later, current technologies have reached international standards. In 2021, the North American Clean Energy Research Center of the Beijing Low-Carbon Clean Energy Research Institute under the State Energy Group developed liquid hydrogen refueling technology based on submerged high-pressure liquid hydrogen pumps, achieving an average refueling rate of 4 kg/min per pump [61].

In technical research related to liquid hydrogen refueling processes, multiple individual devices used during refueling have seen significant technological advancements and development.

(a) Cryogenic Couplings: Cryogenic couplings requiring frequent disassembly during liquid hydrogen refueling are prone to heat leakage, representing a weak link in the entire refueling process. Traditional cryogenic couplings require specialized personnel wearing protective gloves and goggles for operation. Heat leakage may cause freezing between connected pipelines, necessitating heating during disassembly—a process that wastes considerable time. Additionally, components require cleaning after each use. Linde has developed a novel cryogenic coupling (Fig. **12**) that addresses these issues [58]. Under normal conditions, the ball valve within this cryogenic coupling remains closed. It opens only when the corresponding pipelines are connected. Once opened, the coupling forms a sealed tubular volume isolated from the external environment. The cold finger from the hydrogen station side extends through this tubular structure to the vehicle side, establishing a coaxial, well-insulated, and sealed connection between the two coupling sections. The innermost pipeline within this connection structure transports cryogenic liquid hydrogen from the refueling station to the vehicle's liquid hydrogen tank. The outer coaxial pipeline guides exhaust gas back to the refueling station. Upon completion of the liquid hydrogen tank filling, the cold finger retracts to a secure position within the cryogenic coupling on the station side. Only after the cold finger is fully retracted can the ball valve close, allowing the cryogenic coupling to be disconnected from the vehicle. This decoupling process requires no preheating or cleaning, enabling immediate initiation of the next filling cycle without additional waiting time between consecutive operations.

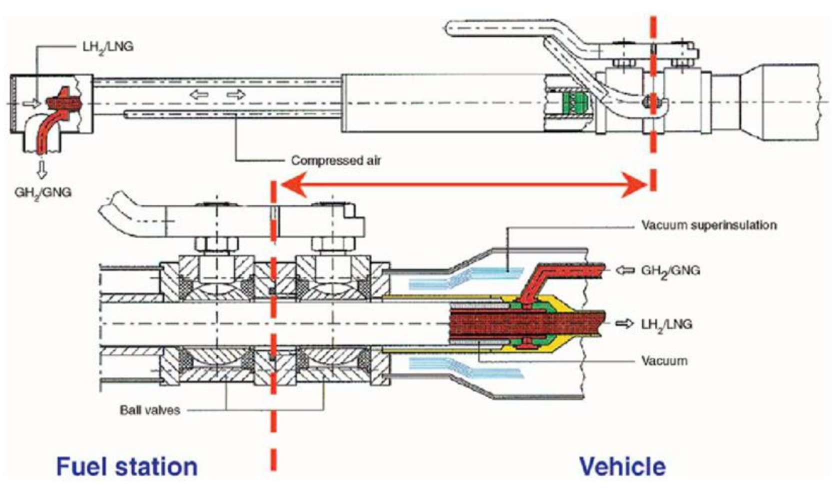


Figure 12: Schematic diagram of the cryogenic coaxial coupling developed by linde company [58].

(b) Liquid Hydrogen Refueling Machines and Nozzles: The primary manufacturers of liquid hydrogen refueling machines in the United States are Plug Power and Air Products. Iwatani Corporation of Japan has independently developed liquid hydrogen refueling machines and nozzles that are already in practical application at hydrogen refueling stations. The main manufacturer of hydrogen nozzles in Germany is Linde. The independently developed liquid hydrogen refueling nozzles by Linde and Nitto Corporation of Japan are shown in Fig. (**13**) [62]. Research on liquid hydrogen refueling products for domestic hydrogen stations remains scarce, particularly the lack of testing standards for civilian liquid hydrogen, which severely hinders the development of liquid hydrogen nozzles. Currently, Zhongke Fuhai has established China's first commercial liquid hydrogen refueling station in Guangdong by importing hydrogenation equipment from the United States. Additionally, Furui Hydrogen Energy plans to independently develop liquid hydrogen dispensers and nozzles, advancing domestic liquid hydrogen refueling technology. The Beijing Aerospace Testing Technology Research Institute has independently developed the liquid hydrogen dispensing nozzle shown in Fig. (**14**). This product was exhibited at the China International Aviation & Aerospace Exhibition and has reached mass production levels. It fills a critical technological gap in key components for liquid hydrogen refueling stations in China and successfully breaks through foreign technical barriers [63].

(**a**) Linde Liquid Hydrogen Refueling Nozzle (**b**) Nitto Liquid Hydrogen Refueling Nozzle

Figure 13: Actual image of liquid hydrogen refueling nozzle [63].

Figure 14: Liquid hydrogen refueling nozzle developed by the Beijing Aerospace Testing Research Institute [63].

The refueling process for liquid hydrogen nozzles typically includes: connecting the nozzle to the vehicle's hydrogen inlet, gas purging, liquid hydrogen refueling, nozzle disengagement, recovery, pressure testing, disconnecting the nozzle from the vehicle inlet, and self-sealing of the nozzle tip and vehicle inlet. Currently, the technical challenges of liquid hydrogen refueling nozzles [62] primarily lie in: (1) Ensuring the realization of distinct functions during each refueling stage, which imposes stringent requirements on the internal structural design of the nozzle; (2) Significant heat leakage during liquid hydrogen refueling can cause vaporization, potentially creating safety hazards. Therefore, the nozzle must maintain excellent thermal insulation while minimizing its volume and weight; (3) Post-refueling, frost may form on the nozzle tip, potentially freezing it during subsequent refueling or transferring frost into the vehicle's liquid hydrogen storage tank, compromising refueling safety. Consequently, frost removal functionality at the nozzle tip must be incorporated into the design.

(c) Vehicle-mounted liquid hydrogen pumps: In terms of liquid hydrogen pump technology, these pumps were initially primarily used in aerospace and military applications for transporting cryogenic propellant fuels, and have gradually expanded into the civilian liquid hydrogen fuel vehicle sector. Pumps suitable for cryogenic systems include bellows pumps, centrifugal pumps, and piston pumps. However, bellows pumps exhibit low efficiency and short service life, while centrifugal pumps have limited single-stage pressure and are unsuitable for placement inside liquid hydrogen Dewars. Consequently, reciprocating piston pumps—which offer stable flow rates and can generate significant pressure differentials—are the most suitable choice for liquid hydrogen pumping. As early as the 1980s, BMW successfully applied a compact liquid hydrogen piston pump in the fuel delivery system of its liquid hydrogen fuel cell vehicles. This hydraulically driven pump achieved a maximum pressure of 2.5 MPa with a cooling time under 5 minutes [64]. In 2012, the U.S. Lawrence Livermore National Laboratory collaborated with Linde to develop a high-pressure liquid hydrogen pump for refueling applications [65]. Linde's high-pressure liquid hydrogen piston pump achieves a maximum refueling capacity of 120 kg/h, an outlet pressure of 87.5 MPa, and a flow rate of 30 g/s, while consuming only 0.6 kWh/kg of energy. Zhan Ying designed a novel cryogenic liquid hydrogen pump with a maximum cyclic displacement of 5 L/min and a maximum pressure differential of 0.5 MPa [66]. The submerged liquid hydrogen pump developed by Li Qiang et al. offers the advantage of minimal refueling speed variation with ambient temperature, achieving a flow rate of 6 L/min [67].

Liquid hydrogen piston pump assemblies typically include auxiliary equipment such as prime movers, gear reducers, hydraulic ends, drive ends, lubrication systems, and cooling systems. The drive end primarily supplies power to the hydraulic end, which consists of components including suction and discharge valves, cylinder heads, valve covers, cylinder blocks, valve boxes, cylinder liners, inlet/outlet flanges, and pistons. The reciprocating motion of the piston, driven by the piston rod, induces periodic volume changes within the pump chamber. This volumetric variation synchronizes with the opening and closing cycles of the inlet and outlet valves, thereby achieving the pump's function of drawing in and discharging liquid hydrogen [68]. Fig. (**15**) displays a cryogenic liquid hydrogen pump used for refueling liquid hydrogen fuel vehicles [69]. Additionally, Lawrence Livermore National Laboratory in the United States conducted performance tests using a liquid hydrogen pump

Figure 15: Actual image of cryogenic liquid hydrogen pump. [69].

manufactured by Linde. This pump can extract liquid hydrogen from a container at a pressure of 0.3 MPa and a low temperature of 25 K, achieving a flow rate of up to 100 kg/h. A schematic diagram of this liquid hydrogen pump is shown in Fig. (**16**) [70].

Current liquid hydrogen pump technology still faces several key technical challenges [68]: (1) Sealing issues: Gaps between the piston and cylinder in liquid hydrogen pumps cause significant leakage during operation, reducing volumetric efficiency; (2) Wear issues: Friction between the piston and cylinder leads to wear on piston or piston rod seals, necessitating the selection of highly wear-resistant materials and specialized processing to minimize material degradation; (3) Liquid Hydrogen Vaporization: Heat leakage from the external environment and friction-generated heat within the pump cause cooling capacity loss in liquid hydrogen, reducing pump efficiency or triggering cavitation. Minimizing cooling capacity loss of the liquid hydrogen fluid within the pump is therefore essential. Currently, the development of cryogenic liquid hydrogen pumps in China remains in its infancy, lacking a mature production system. The country continues to rely heavily on imported liquid hydrogen pump products, which has become a significant factor limiting the commercialization and development of liquid hydrogen fuel vehicles domestically.

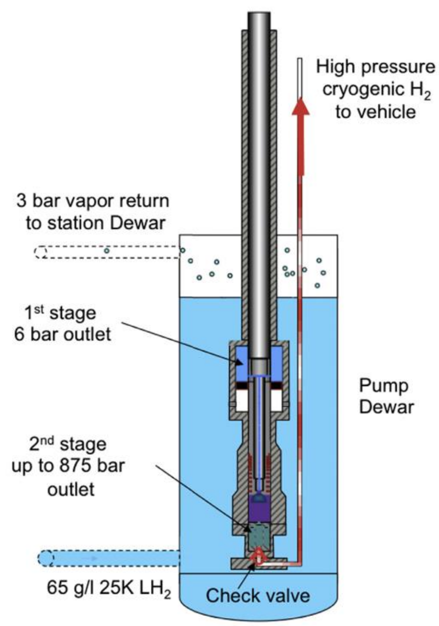


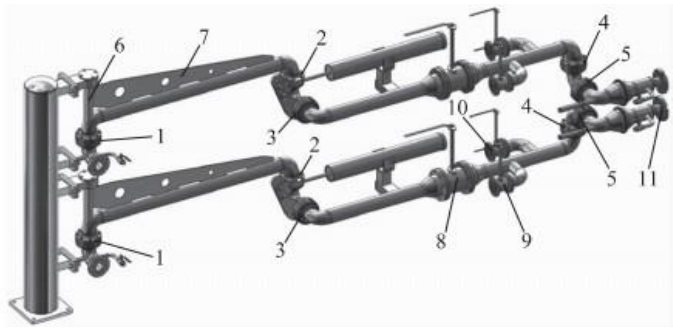
Figure 16: Schematic diagram of liquid hydrogen pump. Structure [70].

(d) Liquid Hydrogen Loading Arm: The structure of the liquid hydrogen loading arm primarily consists of the liquid arm, vapor arm, and vertical shaft. The liquid arm is mainly used to inject liquid hydrogen into the liquid hydrogen fuel tanks of liquid hydrogen fuel vehicles, while the vapor arm recovers the vaporized gas (BOG) from the liquid hydrogen tanks. The vertical shaft and pull plate form the support structure for the loading arm. The vapor arm and liquid arm are mounted above and below the vertical shaft, respectively. Valves control the opening and closing of the pipelines for both arms. Both arms can rotate freely around the vertical shaft through swivel joints to any angle, enabling vehicle connection and refueling at any position via the arm-end interfaces. A three-dimensional model of the liquid hydrogen loading arm is shown in Fig. (**17**) [71].

4.3. Liquid Hydrogen Vaporization Hydrogen Supply System

Pressure stabilization control during fuel hydrogen supply is one of the key technologies for onboard liquid hydrogen storage and supply systems. Liquid hydrogen fuel is typically stored in vehicle-mounted cryogenic tanks in a low-temperature liquid state. It cannot be directly supplied to power systems such as fuel cells. Before entering the power system, liquid hydrogen must undergo heating and vaporization in a vaporizer, along with corresponding temperature and pressure regulation. Only by maintaining the pressure of the vehicle-mounted liquid hydrogen cylinder within a reasonable range can a stable hydrogen flow be supplied to the power system

[72, 73]. Therefore, it is necessary to study pressure stabilization methods during the fuel supply process. Existing common pressure stabilization methods for the fuel supply process typically include: self-generated pressurization from the vaporizer, partial gas recirculation heat exchange pressurization, liquid hydrogen pump pressurization, built-in electric heating pressurization, gas compressor pressurization, and thermal amplifier pressurization [74-76]. The working principles and comparative advantages/disadvantages of each stabilization method are shown in Table **3**, while schematic diagrams of each method are presented in Fig. (**18**).



1～5- Rotary joint；6- Vertical scroll；7- Pull plate；8～10- Valve；11- Interface

Figure 17: Schematic diagram of the liquid hydrogen loading arm 3D model [71].

Table 3: Pressure stabilization methods during gas supply process [76].

Method	Working Principle	Schematic Diagram	Advantages	Disadvantages
Vaporizer self-boosting	The hydrogen vaporized by heating within the heat exchanger is transported to the air cushion space of the liquid hydrogen cylinder for pressurization.	Fig. (**18a**)	The device has a relatively simple structure.	The driving force may be insufficient.
Partial Gas Recirculation Heat Exchange Boosting	A portion of the hydrogen gas, after being vaporized and heated in the heat exchanger, re-enters the vessel via a bypass loop. Within the heat exchanger tubes, it exchanges heat with the liquid hydrogen in the vessel, increasing the evaporation rate of the liquid hydrogen to achieve pressurization.	**Error! Reference source not found.**Fig. (**18b**)	(1) High reliability with intact container sealing structure; (2) The energy for reflux hydrogen is primarily supplied by cooling water or ambient temperature.	The driving force may be insufficient.
Liquid Hydrogen Pump Boosting	Directly supply inlet pressure via liquid hydrogen pump	Fig. (**18c**)	(1) Self-adjusting outlet pressure for liquid hydrogen pumps; (2) Excellent dynamic response; (3) No requirement for high liquid hydrogen tank pressure.	(1) The system structure is relatively complex, posing significant development challenges; (2) Liquid hydrogen pumps consume substantial energy; (3) No mature liquid hydrogen pump products are currently available domestically.
Built-in electric heating booster	The electrical energy generated by the battery is used to heat the heating element inside the liquid hydrogen container. Under the heating effect of the heating element, the liquid hydrogen inside the container evaporates to increase pressure.	Fig. (**18d**)	The boost effect is significant.	(1) The heating wire penetrates the container wall, making it prone to failure due to external gases entering the vacuum layer; (2) It involves additional energy consumption.
Gas Compressor Boosting	Hydrogen gas obtained by heating and vaporizing liquid hydrogen through a water bath heat exchanger using a gas compressor is transported into the liquid hydrogen container for pressurization.	Fig. (**18e**)	Boosting effect is quite good	Additional low-temperature gas compressors are required.
Thermal Amplifier Boosting	When heated, hydrogen storage metals release trace amounts of hydrogen gas, causing a reduction in the vacuum level within the vacuum jacket and an increase in heat leakage from the container.	Fig. (**18f**)	Requires minimal additional energy consumption	Boosting speed is relatively slow, and the effect is not significant.

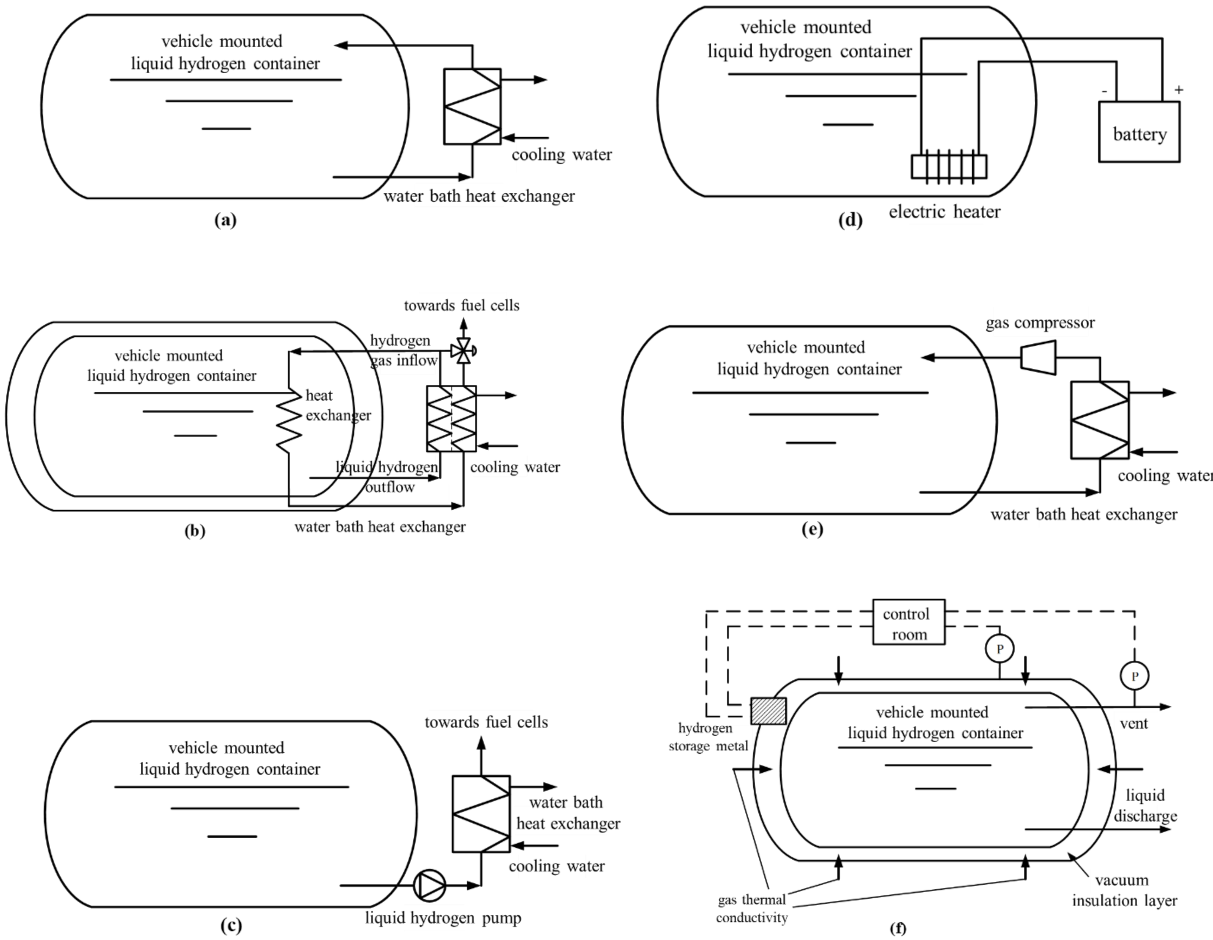


Figure 18: Schematic diagram of pressure control methods during gas supply process [76].

4.4. Exhaust System

To maintain stable pressure within liquid hydrogen cylinders, venting of the cylinders is required during the operation of liquid hydrogen fuel cell vehicles [77]. Due to hydrogen's flammability, venting systems for these vehicles must prioritize safety considerations. Typically, stringent requirements are imposed on ventilation, alarm systems, and fire prevention within the venting system, supplemented by additional measures to minimize the likelihood and consequences of hydrogen leaks. However, beyond safety considerations, the venting system design for liquid hydrogen fuel vehicles must also address the recovery and reuse of the cooling energy from the evaporated gases in the vented stream. This represents a significant technical challenge that cannot be overlooked in the system's design [78].

During storage in containers, liquid hydrogen readily evaporates due to external heat leakage, causing continuous pressure buildup within the tank [79]. To ensure operational safety, vapor cooling screens [80] are commonly employed to absorb the cooling energy from evaporated gases in the exhaust. This reduces container heat leakage, minimizes hydrogen evaporation, and extends the undamaged storage duration of liquid hydrogen tanks. As shown in Fig. (**19**) [81], during the venting process of a liquid hydrogen cylinder, BOG gas flows out from the exterior of the liquid hydrogen filling sleeve. It then circulates around the cylinder through the inner piping of the dual vapor cooling screen, converges, and subsequently exits via the outer piping of the dual vapor cooling screen.

Fig. (**20**) shows a 6 L liquid hydrogen tank for a drone [82]. The tank body is axially supported and fixed, employing vacuum multi-layer insulation combined with a vapor cooling screen for thermal insulation. BOG gas inside the tank flows through a 6 mm pipe, passes through the vapor cooling screen, and is vented outside the tank before being directed to the fuel cell system to generate power. This approach can also serve as a technical reference for liquid hydrogen fuel commercial vehicles.

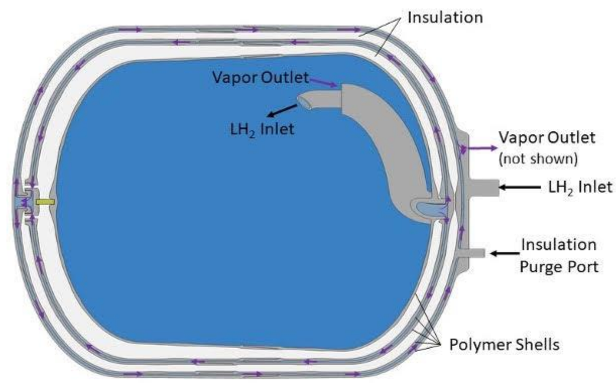


Figure 19: Schematic diagram of liquid hydrogen cylinder venting [81].

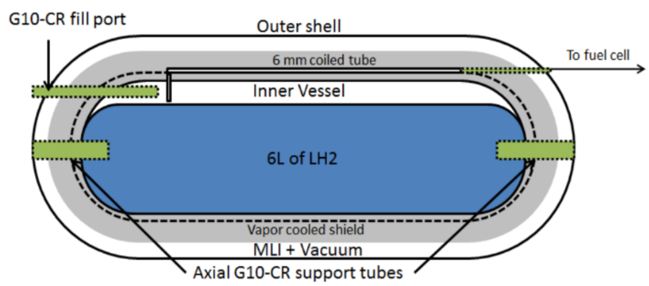


Figure 20: 6 L UAV liquid hydrogen cylinder [82].

The key technologies and development directions of the storage and supply system for commercial vehicles using liquid hydrogen fuel are summarized and organized as shown in the Table **4**. It includes a side-by-side comparison of four key technologies (storage, supply, refueling, and venting), and proposes clear research directions for the development bottlenecks in each technical field.

5. Industry Standards

Relevant domestic and international industry standards are shown in Table **5**. As indicated in the table, early domestic standards for liquid hydrogen applications primarily focused on military sectors, with limited standards for civilian use. It was not until after 2021 that a comprehensive standard system for civilian liquid hydrogen applications was gradually established and refined. As early as 2005, the General Armament Department of the People's Liberation Army issued the National Military Standard “Safety Application Guidelines for Liquid Hydrogen.” In 2014, the General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ) correspondingly released the national standard “Interfaces for Liquid Hydrogen Vehicle Fueling Systems” [83]. By 2021, the National Technical Committee for Hydrogen Energy Standardization successively published “Fuel for Hydrogen Vehicles - Liquid Hydrogen,” “Technical Specifications for Liquid Hydrogen Production Systems,” and “Safety Technical Requirements for Liquid Hydrogen Storage and Transportation,” thereby establishing the preliminary framework for China's civil liquid hydrogen standards system. Subsequently, in 2022, the Hazardous Chemicals Storage Working Committee of the China Technical Supervision Information Association released the “Technical Requirements for Fixed Vacuum Insulated Liquid Hydrogen Pressure Vessels and Projects” and completed the drafting of the “Special Technical Requirements for Mobile Vacuum Insulated Liquid Hydrogen Pressure Vessels,” which took effect in 2023. Additionally, the China Industrial Gases Industry Association successively released the “Safety Technical Specifications for Liquid Hydrogen Dewars,” “Safety Technical Specifications for Vehicle-Mounted Liquid Hydrogen Systems,” and “Safety Technical Specifications for the Use of Liquid Hydrogen Refueling Machines” in 2022, laying the foundation for the development of China's civil liquid hydrogen industry. In January 2023, the

Guangdong Special Equipment Industry Association successively released the group standards Liquid Hydrogen Cylinders—Part 1: Design, Manufacturing, Inspection, and Testing and Liquid Hydrogen Cylinders—Part 2: Operational Requirements, further filling gaps in China's industry standard references for the civilian liquid hydrogen sector. International development of civilian liquid hydrogen technology began earlier, resulting in numerous existing global standards. The International Organization for Standardization (ISO) published the standards Liquid Hydrogen—Road Vehicle Refueling System Interfaces in 1999 and Liquid Hydrogen—Road Vehicle Fuel Tanks in 2006 [34]. Subsequently, the European Automobile Directive, the United Nations Economic Commission for Europe, Russia, the Compressed Gas Association (CGA) of the United States, the Society of Automotive Engineers (SAE) of the United States, and the European Industrial Gases Association (EIGA) also successively released relevant civil liquid hydrogen standards [85-88], providing important support for the application and development of liquid hydrogen in the civil sector.

Table 4: Summary of key technologies and future directions for the storage and supply system of liquid hydrogen-fueled commercial vehicles.

Core Technology	Representative Techniques/Methods	Current Representative Performance Indicators	Key Future Research Directions
Vehicle-Mounted Liquid Hydrogen Cylinders	① High-Vacuum MLI + Vapor-Cooled Shield (VCS) ② Low heat-leak support structure (point-contact) ③ Double-walled (Inner liner: 316L SS/Al alloy; Outer: Carbon-fiber wrapping)	① Daily evaporation rate: ≤6%/day (BAIC Foton, 2022); Early 1-2%/day (MVE, Linde) ② Max. working pressure: 1.6 MPa (BAIC Foton) ③ Storage system weight: 30-110 kg (for 443-1109 L volume)	① Novel lightweight cryogenic materials (alloy brittleness-ductility transition) ② Multi-layer composite insulation optimization (VCS configuration) ③ Anti-slosh & lightweight synergy design ④ Precise liquid level & health monitoring
Vaporization & Pressure Control	① Vaporizer self-pressurization ② Liquid hydrogen pump (reciprocating piston) ③ Thermal amplifier boosting	① Pump outlet pressure: 87.5 MPa (Linde) ② Pump flow rate: 100 kg/h (Linde, tested by LLNL) ③ Energy consumption: 0.6 kWh/kg-H_2	① Long-life, low-wear sealing technology ② High dynamic response flow/pressure decoupling control ③ Integrated supply module (reduced size & weight)
Liquid Hydrogen Refueling	① Cryogenic coaxial coupling (Linde) ② Submerged high-pressure LH2 pump refueling ③ Loading arm (liquid & vapor dual-arm)	① Avg. refueling speed: 4 kg/min (National Energy Group, single pump) ② Refueling time: 1.5 min (120 L tank, early German station)	① High-reliability, self-defrosting nozzle design ② Low loss, fast refueling strategy (reducing 5%-10% boil-off) ③ Domestic production of core components (flow meters, cryogenic valves)
Exhaust & Cold Energy Recovery	① Double VCS (DVCS/SVCS) exhaust line design ② BOG cold energy utilization for fuel cell system or HVAC	① SVCS can reduce heat leak by 60% (Babac, numerical study) ② Cold energy recovery can reduce air compressor power (Yang et al.)	① Efficient, compact BOG cold energy cascade-utilization system ② Onboard integrated Zero Boil-off storage system ③ System-level energy efficiency optimization with cold recovery.

6. Technical Challenges and Future Development Directions

The China Hydrogen Energy and Fuel Cell Industry White Paper indicates [89] that China's annual production of hydrogen fuel cell vehicles will reach 5.2 million units by 2050. By 2060, China's annual hydrogen demand is projected to increase to approximately 1.3×10^8 tons, with renewable energy-based hydrogen production expected to reach 1×10^8 tons, accounting for about 20% of terminal consumption [90]. Domestic market demand for liquid hydrogen fuel commercial vehicles is clearly on an upward trajectory, positioning these vehicles as a key future development direction in the new energy vehicle sector. However, achieving large-scale commercialization of liquid hydrogen fuel commercial vehicles currently faces numerous technical challenges [91], requiring further in-depth exploration and research. Therefore, this paper summarizes the primary technical challenges currently hindering the commercial application of liquid hydrogen fuel vehicles and proposes subsequent development directions.

Table 5: Relevant industry standards at home and abroad.

	Time	Standard	Note
Domestic	2005	GJB 5405-2005《Safety Application Guidelines for Liquid Hydrogen》	Issued by the General Armament Department of the People's Liberation Army of China and already implemented
	March 2014	GB/T30719-2014《Liquid Hydrogen Vehicle Fueling System Interface》[83]	The General Administration of Quality Supervision, Inspection and Quarantine issued and began implementing
	January 2021	T/CCGA40001-2019《liquid hydrogen》	The China Industrial Gases Industry Association has issued and implemented
	March 2021	《Technical Specifications for Hydrogen Refuelling Stations》GB50516-2010（2021 Edition）[84]	The Ministry of Housing and Urban-Rural Development has issued an announcement regarding partial amendments.
	November 2021	GB/T40045-2021《Liquid hydrogen fuel for hydrogen-powered vehicles》	The National Technical Committee for Hydrogen Energy Standardization has organized the development and has commenced implementation.
		GB/T40061-2021《Technical Specifications for Liquid Hydrogen Production Systems》	
		GB/T40060-2021《Technical Requirements for Liquid Hydrogen Storage and Transportation》	
	March 2022	T/CATSI 05006-2021《Fixed Vacuum Insulated Liquid Hydrogen Pressure Vessel and Project Technical Requirements》	The Working Committee on Hazardous Chemical Storage of the China Technical Supervision Information Association has issued and implemented the following:
		T/CCGA 40011-2021《Safety Technical Specifications for Liquid Hydrogen Dewars》	The China Industrial Gases Association announced that implementation has commenced.
		T/CCGA 40009-2021《Safety Technical Specifications for Vehicle-Mounted Liquid Hydrogen Systems》	
		T/CCGA 40010-2021《Technical Specifications for the Safe Use of Liquid Hydrogen Refueling Machines》	
	January 2023	T/GDASE 0033.1-2022《Liquid Hydrogen Cylinders—Part 1: Design, Construction, Inspection, and Testing》	Guangdong Provincial Special Equipment Industry Association Releases
		T/GDASE 0033.2-2022《Liquid Hydrogen Cylinders—Part 2: Operational Requirements》	
		T/CATSI 05007-2023《Special Technical Requirements for Mobile Vacuum Insulated Liquid Hydrogen Pressure Vessels》	The China Association for Technical Supervision Information has announced that implementation has commenced.
International	1999	《Liquid hydrogen–land vehicle fueling system interface》[**Error! Reference source not found.**]	The International Organization for Standardization (ISO) has released
	2006	ISO 13985《Liquid hydrogen–land vehicle fuel tanks》[83]	The International Organization for Standardization (ISO) has released
	2010	No.406/2010-EU《Implementing Regulation (EC)No.79/2009 of the European parliament and of the council on type-approval of hydrogen-powered motor vehicles》[85]	European Automobile Directive
	2013	《GTR13：Global technical regulation on hydrogen for fuel cell vehicles》[86]	Prepared by the United Nations Economic Commission for Europe
	2014	ГОСТР 56248-2014《Technical conditions of liquid hydrogen》[87]	Russian State Standard
	2014	CGA P-28-2014《Risk management plan guidance document for bulk liquid hydrogen systems》[87]	Compressed Gas Association (CGA)
	2018	SAE J 2579-2018《Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles》[88]	Society of Automotive Engineers
	2019	Doc 06/19《Safety in storage, handling and distribution of liquid hydrogen》[87]	European Industrial Gases Association (EIGA)

(1) On-board liquid hydrogen tanks require further design optimization. The liquid hydrogen tank system poses significant challenges for vehicle space allocation, features complex vaporization and pressurization systems, and presents difficulties in liquid level measurement. Unreasonable structural design and spatial layout can increase heat leakage from the tanks, compromising the long-term, undamaged storage of liquid hydrogen fuel and potentially affecting the operational safety of liquid hydrogen fuel vehicles. For vehicle-mounted liquid hydrogen tanks, material development must advance toward new cryogenic materials that reduce tank mass, enhance mechanical strength, and lower production costs. Structural design must also evolve to improve thermal insulation, operational stability, safety monitoring capabilities, and refueling speed.

(2) Despite its clear advantages over gaseous hydrogen, liquid hydrogen retains drawbacks such as low density, high volatility, and storage challenges. To extend the undamaged storage time of onboard cryogenic tanks, new commercial vehicle technologies utilizing supercooled liquid hydrogen or slurry hydrogen as fuel can be developed. Employing supercooled liquid hydrogen or even slurry hydrogen offers greater heat capacity and volumetric cooling energy, presenting a potential solution to this challenge. Research institutions like NASA have conducted extensive experimental studies on supercooled liquid hydrogen and slurry hydrogen for aerospace applications [92-94]. Researchers at Xi'an Jiaotong University in China have also conducted relevant experiments and numerical simulations on slush hydrogen [95, 96]. Furthermore, recognizing the significant advantages of supercooled liquid hydrogen over standard liquid hydrogen, Daimler Trucks and Linde have partnered to explore using supercooled liquid hydrogen as a vehicle fuel, aiming to achieve longer ranges for liquid hydrogen fuel vehicles [97]. Future research can build upon these studies to further develop new fuels for commercial vehicles.

(3) Research on core components for domestic hydrogen refueling equipment remains relatively scarce, with key devices still primarily reliant on imports. Therefore, in developing hydrogen refueling equipment, further research and development are needed for critical components suitable for liquid hydrogen-fueled commercial vehicles. These include cryogenic liquid hydrogen pumps, high-precision hydrogen mass flow meters, sensors, highly reliable refueling nozzles, heat exchangers, and cryogenic valves designed for liquid hydrogen environments. This will accelerate the localization of core components. Additionally, significant losses occur during the refueling process. Even when using vacuum-insulated refueling hoses, 5%–10% of liquid hydrogen is lost through vaporization. This necessitates further improvements in the sealing and insulation performance of refueling equipment like nozzles to reduce fuel losses during refueling.

(4) During operation, liquid hydrogen fuel vehicles encounter scenarios such as emergency acceleration, braking, and cornering. Due to liquid hydrogen's low viscosity, significant sloshing occurs within the tank under these harsh conditions. This not only causes unstable internal pressure but also subjects the tank's support structures and monitoring equipment to impact forces, potentially damaging structural components in severe cases. Therefore, the impact of inertial forces on liquid hydrogen cylinders must be considered prior to designing vehicle-mounted liquid hydrogen containers. While researchers have extensively studied liquid sloshing behavior and the effectiveness of anti-sloshing plates in ambient-temperature or cryogenic LNG tankers under accelerations like 2g and 5g, research on the sloshing characteristics of liquid hydrogen in vehicle-mounted cylinders under significant excitation remains limited. Consequently, adapting the structural design of liquid hydrogen cylinders to withstand harsh operating conditions remains a critical technical challenge. This necessitates further investigation into the thermodynamic parameter variations within containers during significant hydrogen sloshing, thereby providing a reference basis for the structural design of vehicle-mounted liquid hydrogen cylinders.

(5) Further R&D is needed on cold energy storage and recovery technologies for vehicle-mounted liquid hydrogen systems to enhance energy utilization efficiency. Current research has explored the recovery of liquid hydrogen cold energy and boil-off gas (BOG). The liquid hydrogen cold energy recovery system shown in Fig. (**21**) [98] reduces air compressor power consumption, shrinks intermediate cooler dimensions, and lowers pump and radiator fan power requirements. The BOG recovery system for liquid hydrogen storage and supply designed by researchers [24] (Fig. **22**) utilizes the endothermic properties of liquid hydrogen vaporization to absorb part of the heat dissipation pressure from the fuel cell system, enabling cold energy utilization. Future research should focus on deeper development in cold energy recovery, exploring more efficient and diversified cold energy utilization methods to maximize energy utilization efficiency.

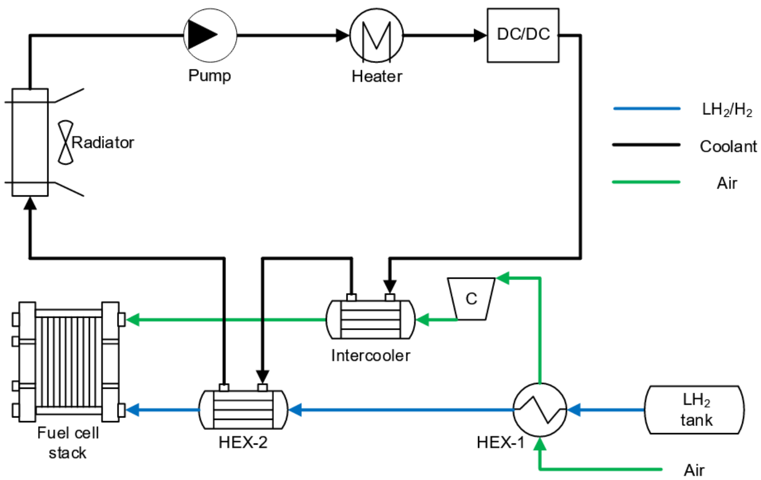


Figure 21: Liquid hydrogen cold energy utilization system for fuel cell heavy-duty trucks [98].

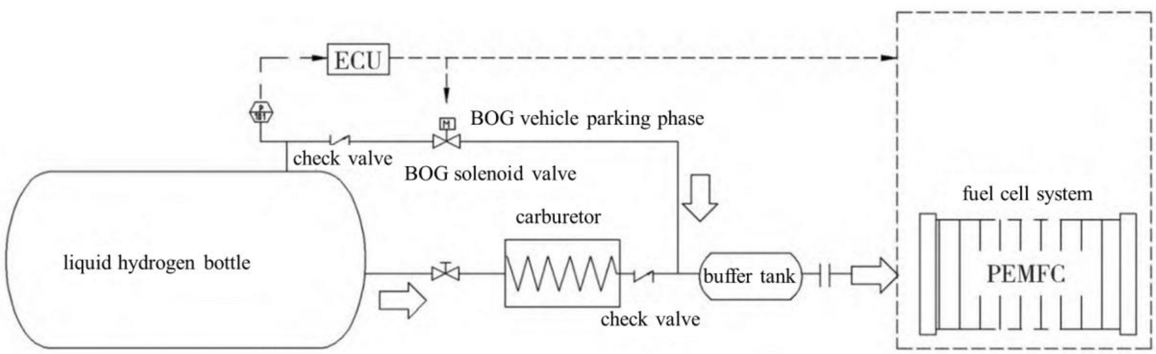


Figure 22: Liquid hydrogen storage and supply system BOG recovery system diagram [24].

(6) Relevant laws, regulations, and standards in the field of civil liquid hydrogen applications remain urgently in need of refinement. Efforts should be made to further elaborate and improve laws and regulations pertaining to hydrogen energy utilization. Corresponding legislation should be enacted, including Hydrogen Storage Management Laws, Hydrogen Safety Laws, Hydrogen Fuel Fire Protection Laws, and Liquid Hydrogen Fuel Vehicle Safety Management Laws. This will provide legal and institutional support and safeguards for the application and development of liquid hydrogen fuel commercial vehicles [99]. Regarding industry standards, efforts should continue to develop and refine standards for hydrogen energy applications, standardizing the production and use of liquid hydrogen fuel commercial vehicles to ensure liquid hydrogen applications are grounded in established guidelines. Additionally, it is necessary to enhance public awareness of scientific knowledge concerning the safe application of liquid hydrogen, boost confidence in its safety, and accelerate the construction of large-scale liquid hydrogen refueling stations [100] to facilitate the widespread adoption and promotion of liquid hydrogen fuel vehicles.

7. Conclusion

In conclusion, liquid hydrogen fuel is a vital pathway for future zero-emission commercial vehicles due to its high cost-effectiveness in long-distance transport. This systematic analysis reveals that current heavy-duty trucks, represented by the Mercedes-Benz GenH2 and China's "New Long March 1", have achieved performance milestones of 1000 km range with an 80 kg-class hydrogen storage system, confirming the technical viability of the liquid hydrogen approach. However, compared to developed nations like the U.S., Germany, and Japan, China's liquid hydrogen commercial vehicle industry remains nascent. The core technical challenges hindering large-scale commercialization are concentrated in three areas: (1) Insulation and lightweight design of onboard tanks, requiring new cryogenic materials and advanced insulation structures like vapor-cooled shields to further reduce evaporation rates and extend dormancy; (2) Domestic production of core refueling equipment, where the independent development of liquid hydrogen pumps and highly reliable refueling nozzles is imperative to reduce costs and secure the supply chain; (3) Safety control under harsh conditions, demanding in-depth investigation into the severe sloshing characteristics of liquid hydrogen under emergency braking and turning, along with the development of efficient boil-off gas cold energy recovery systems to enhance overall vehicle energy efficiency. Overcoming these challenges will be the key to transitioning China's liquid hydrogen fuel commercial vehicles from demonstration to commercial reality.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Chen K, Lau MY, Luo X, Huang J, Ouyang L, Yang XS. Research progress in solid-state hydrogen storage alloys: a review. J Mater Sci Technol. 2026; 246: 256-89. http://doi.org/10.1016/j.jmst.2025.05.037

[2] Wei K, Shi P, Zong H, Qin Y. Research on the development of key technologies in the hydrogen energy industry. In: 2025 4th International Conference on Smart Grid and Green Energy (ICSGGE); 2025. p. 44-9. http://doi.org/10.1109/ICSGGE64667.2025.10984696

[3] Srivastava S. Hydrogen storage materials for vehicular applications. Energy Storage. 2024; 6(1): e524. http://doi.org/10.1002/est2.524

[4] Zheng J, Liu X, Xu P, Liu P, Zhao Y, Yang J. Development of high pressure gaseous hydrogen storage technologies. Int J Hydrogen Energy. 2012; 37(1): 1048-57. http://doi.org/10.1016/j.ijhydene.2011.02.125

[5] Orlova S, Mezeckis N, Vasudev VPK. Compression of hydrogen gas for energy storage: a review. Latv J Phys Tech Sci. 2023; 60(2): 4-16. http://doi.org/10.2478/lpts-2023-0007

[6] Galassi MC, Acosta-Iborra B, Baraldi D, Bonato C, Harskamp F, Frischauf N, *et al*. Onboard compressed hydrogen storage: fast filling experiments and simulations. Energy Procedia. 2012; 29: 192-200. http://doi.org/10.1016/j.egypro.2012.09.024

[7] Aceves SMBG, Rambach GD. Insulated pressure vessels for hydrogen storage on vehicles. Int J Hydrogen Energy. 1998; 23(7): 583-91. http://doi.org/10.1016/S0360-3199(97)00079-7

[8] Aceves SM, Espinosa-Loza F, Ledesma-Orozco E, Ross TO, Weisberg AH, Brunner TC, *et al*. High-density automotive hydrogen storage with cryogenic capable pressure vessels. Int J Hydrogen Energy. 2010; 35(3): 1219-26. http://doi.org/10.1016/j.ijhydene.2009.11.069

[9] Ahluwalia RK, Hua TQ, Peng JK. On-board and off-board performance of hydrogen storage options for light-duty vehicles. Int J Hydrogen Energy. 2012; 37(3): 2891-910. http://doi.org/10.1016/j.ijhydene.2011.05.040

[10] Hwang HT, Varma A. Hydrogen storage for fuel cell vehicles. Curr Opin Chem Eng. 2014; 5: 42-8. http://doi.org/10.1016/j.coche.2014.04.004

[11] Durbin DJ, Malardier-Jugroot C. Review of hydrogen storage techniques for on board vehicle applications. Int J Hydrogen Energy. 2013; 38(34): 14595-617. http://doi.org/10.1016/j.ijhydene.2013.07.058

[12] Felderhoff M, Weidenthaler C, von Helmolt R, Eberle U. Hydrogen storage: the remaining scientific and technological challenges. Phys Chem Chem Phys. 2007; 9(21): 2643-53. http://doi.org/10.1039/b701563c

[13] Raucci C, Calleya J, Suarez De La Fuente S, Pawling R. Hydrogen on board ship: a first analysis of key parameters and implications. In: International Conference on Shipping in Changing Climates 2015. University of Strathclyde; 2015.

[14] Zhu QJ, Zhu JZ. Development and prospect of liquid hydrogen refueling stations in China. Gas Heat. 2020; 40(7): 15-19. http://doi.org/10.13608/j.cnki.1000-4416.2020.07.014

[15] Gurz M, Baltacioglu E, Hames Y, Kaya K. The meeting of hydrogen and automotive: a review. Int J Hydrogen Energy. 2017; 42(36): 23334-46. http://doi.org/10.1016/j.ijhydene.2017.02.124

[16] Aasadnia M, Mehrpooya M. Large-scale liquid hydrogen production methods and approaches: a review. Appl Energy. 2018; 212: 57-83. http://doi.org/10.1016/j.apenergy.2017.12.033

[17] Introduction: hydrogen, energy and environment. In: Hydrogen Technologies for Energy. p. 1-21. http://doi.org/10.1049/PBPO205E_ch1

[18] Ugurlu A, Oztuna S. How liquid hydrogen production methods affect emissions in liquid hydrogen powered vehicles? Int J Hydrogen Energy. 2020; 45(60): 35269-80. http://doi.org/10.1016/j.ijhydene.2020.01.250

[19] Yang Y, Lin L, Bao W. Development of standards for liquid hydrogen in China. IOP Conf Ser Earth Environ Sci. 2022; 1011(1): 012001. http://doi.org/10.1088/1755-1315/1011/1/012001

[20] Chen L, Wang Y, Jiang Y. Life cycle assessment of liquid hydrogen fuel for vehicles with different production routes in China. Energy. 2024; 299: 131472. http://doi.org/10.1016/j.energy.2024.131472

[21] Zhao XL. Strategic significance of hydrogen FCEV to petrochemical enterprises. Pet Petrochem Today. 2019; 27(1): 15-19.

[22] Chen Y, Sequeira CAC, Chen C, Wang X, Wang Q. Metal hydride beds and hydrogen supply tanks as minitype PEMFC hydrogen sources. Int J Hydrogen Energy. 2003; 28(3): 329-33. http://doi.org/10.1016/S0360-3199(02)00064-2

[23] Sun DL. Development and challenge for on-board hydrogen storage. Chin J Nat. 2011; 33(1): 13-8.

[24] Li H, Hu ZY, Hu JY. Design, analysis and validation of novel distributed drive liquid hydrogen fuel cell heavy commercial vehicles. Automot Eng. 2022; 44(8): 1183-98,1250. http://doi.org/10.19562/j.chinasae.qcgc.2022.08.008

[25] Cui MY, Zhu XP, Xue K. Hydrogen storage technology of hydrogen fuel cell vehicle and its development status. Automob Appl Technol. 2022; 47(10): 173-8. http://doi.org/10.16638/j.cnki.1671-7988.2022.010.036

[26] Olsson R, Cameron C, Moreau F, Marklund E, Merzkirch M, Pettersson J. Design, manufacture, and cryogenic testing of a linerless composite tank for liquid hydrogen. Appl Compos Mater. 2024; 31(4): 1131-54. http://doi.org/10.1007/s10443-024-10219-y

[27] Escher WJD, Ecklund EE. Survey of liquid hydrogen container technology for highway vehicle fuel system applications. In: 14th Intersociety Energy Conversion Engineering Conference; 1979. Vol. 1. p. 790-5. http://doi.org/10.2172/6320525

[28] Furuhama S, Hiruma M, Enomoto Y. Development of a liquid hydrogen car. Int J Hydrogen Energy. 1978; 3(1): 61-81. http://doi.org/10.1016/0360-3199(78)90057-5

[29] Ustolin F, Campari A, Taccani R. An extensive review of liquid hydrogen in transportation with focus on the maritime sector. J Mar Sci Eng. 2022; 10(9): 1222. http://doi.org/10.3390/jmse10091222

[30] Liang Y, Wang Y, Guo YY. The advance and prospect of liquid hydrogen tank for hydrogen-powered vehicles. Cryogenics. 2001; (5): 31-6.

[31] Michel F, Fieseler H, Meyer G, Theiβen F. On-board equipment for liquid hydrogen vehicles. Int J Hydrogen Energy. 1998; 23(3): 191-9. http://doi.org/10.1016/S0360-3199(97)00044-X

[32] Nie ZS, Li Q, Hong GT. Theoretical and experimental investigation of evaporation rate in vehicle liquid hydrogen dewar. Cryog Eng. 2004; (4): 55-8.

[33] Mori D, Hirose K. Recent challenges of hydrogen storage technologies for fuel cell vehicles. Int J Hydrogen Energy. 2009; 34(10): 4569-74. http://doi.org/10.1016/j.ijhydene.2008.07.115

[34] Wang X. Study on strength and vibration fatigue characteristics of a vehicle-mounted liquid hydrogen cylinder [dissertation]. Lanzhou: Lanzhou University of Technology; 2022. http://doi.org/10.27206/d.cnki.ggsgu.2022.000769

[35] Gao JL, Yuan ZM, Shang HW. Research progress on storage technology and stored energy application of hydrogen. Metall Funct Mater. 2016; 23(1): 1-11. http://doi.org/10.13228/j.boyuan.issn1005-8192.2015060

[36] Wang QF, Wu T, Li X. Study on the law of hydrogen storage density of car liquid hydrogen bottle. Cryog Supercond. 2023; 51(1): 85-9. http://doi.org/10.16711/j.1001-7100.2023.01.013

[37] Qiu Y, Yang H, Tong L, Wang L. Research progress of cryogenic materials for storage and transportation of liquid hydrogen. Metals. 2021; 11(7): 1101. http://doi.org/10.3390/met11071101

[38] Liu W, Du Y. Research status of low temperature titanium alloy. Rare Met Lett. 2007; 26: 6-10.

[39] Qu Y, Yuan X, Xie H. Research and application status and development trend of low temperature titanium alloy. Mech Eng Autom. 2009; (1): 189-91.

[40] Guo J, Zhang G, Chen GH. Research progress on vehicle liquid hydrogen cylinder design. Chem Ind Eng Prog. 2023; 42 (08): 4221-9. http://doi.org/10.16085/j.issn.1000-6613.2022-1764

[41] Rüdiger H. Design characteristics and performance of a liquid hydrogen tank system for motor cars. Cryogenics. 1992; 32(3): 327-9. http://doi.org/10.1016/0011-2275(92)90373-I

[42] Aceves SM, Petitpas G, Espinosa-Loza F, Matthews JM, Ledesma-Orozco E. Safe, long range, inexpensive and rapidly refuelable hydrogen vehicles with cryogenic pressure vessels. Int J Hydrogen Energy. 2013; 38(5): 2481-9. http://doi.org/10.1016/j.ijhydene.2012.11.123

[43] Ma X, Chen S, Wang X, Zhang W, Wang Z, Mi M, *et al*. Insulation excellence and storage dynamics in a 500-litre self-developed vehicular liquid hydrogen cylinder: thermal leakage and status analysis. J Phys Conf Ser. 2024; 2787(1): 012022. http://doi.org/10.1088/1742-6596/2787/1/012022

[44] Krenn A, Desenberg D. Return to service of a liquid hydrogen storage sphere. IOP Conf Ser Mater Sci Eng. 2020; 755(1): 012023. http://doi.org/10.1088/1757-899X/755/1/012023

[45] Jiang W, Sun P, Li P, Zuo Z, Huang Y. Transient thermal behavior of multi-layer insulation coupled with vapor cooled shield used for liquid hydrogen storage tank. Energy. 2021; 231: 120859. http://doi.org/10.1016/j.energy.2021.120859

[46] Yan M, Kang H, Yuan Y, Xu M. Thermal insulation effect and optimized design of VCS for large evaporation liquid hydrogen storage tank. Int J Hydrogen Energy. 2025; 159: 150480. http://doi.org/10.1016/j.ijhydene.2025.150480

[47] Yin H, Chen G, Lv H, Xu Q, Qu S, Zhang G, *et al*. Thermodynamic modeling and analysis of insulation structures for vehicle liquid hydrogen cylinder. J Energy Storage. 2025; 138: 118527. http://doi.org/10.1016/j.est.2025.118527

[48] Mills GL, Buchholtz B, Olsen A. Design, fabrication and testing of a liquid hydrogen fuel tank for a long duration aircraft. In: AIP Conference Proceedings; 2012; 1434(1): 773-80. http://doi.org/10.1063/1.4706990

[49] Sullivan RM, Palko JL, Tornabene RT. Engineering analysis studies for preliminary design of lightweight cryogenic hydrogen tanks in UAV applications [report]. No. E-15431. 2006.

[50] Xu W, Li Q, Huang M. Design and analysis of liquid hydrogen storage tank for high-altitude long-endurance remotely-operated aircraft. Int J Hydrogen Energy. 2015; 40(46): 16578-86. http://doi.org/10.1016/j.ijhydene.2015.09.028

[51] Kim SY, Kang BH. Thermal design analysis of a liquid hydrogen vessel. Int J Hydrogen Energy. 2000; 25(2): 133-41. http://doi.org/10.1016/S0360-3199(99)00020-8

[52] Babac G, Sisman A, Cimen T. Two-dimensional thermal analysis of liquid hydrogen tank insulation. Int J Hydrogen Energy. 2009; 34(15): 6357-63. http://doi.org/10.1016/j.ijhydene.2009.05.052

[53] Miao C, Zhang Y, Huang L. Key technologies of liquid hydrogen container on vehicle. Cryog Supercond. 2022; 50(4): 71-4. http://doi.org/10.16711/j.1001-7100.2022.04.012

[54] Clark NN, McKain DL, Johnson DR. Estimates of emissions from hydrogen transportation fueling infrastructure and vehicles. J Air Waste Manag Assoc. 2025; 75(7): 559-90. http://doi.org/10.1080/10962247.2025.2495811

[55] Otto T, Erhart P, Kraus S, Grube T, Linßen J, Stolten D. Comparing hydrogen refueling concepts for heavy-duty vehicles. Int J Hydrogen Energy. 2024; 110: 115-27. http://doi.org/10.1016/j.ijhydene.2025.01.498

[56] Genovese M, Fragiacomo P. Hydrogen refueling station: overview of the technological status and research enhancement. J Energy Storage. 2023; 61: 106758. http://doi.org/10.1016/j.est.2023.106758

[57] Yao G, Shao Y, Wang W. Design and application of a vehicle mounted liquid hydrogen storage and supply system. In: Atiquzzaman M, Yen N, Xu Z, Eds. Proceedings of the 5th International Conference on Big Data Analytics for Cyber-Physical System in Smart City-Volume 2. Singapore: Springer Nature; 2025. p. 855-65. http://doi.org/10.1007/978-981-96-0211-7_77

[58] Wolf J. Liquid hydrogen technology for vehicles. MRS Bull. 2002; 27(9): 684-7. http://doi.org/10.1557/mrs2002.222

[59] Peschka W. Liquid hydrogen fueled automotive vehicles in Germany-status and development. Int J Hydrogen Energy. 1986; 11(11): 721-8. http://doi.org/10.1016/0360-3199(86)90141-2

[60] Pehr K, Sauermann P, Traeger O, Bracha M. Liquid hydrogen for motor vehicles - the world's first public LH2 filling station. Int J Hydrogen Energy. 2001; 26(7): 777-82. http://doi.org/10.1016/S0360-3199(00)00128-2

[61] Developed by the National Energy Group! The world's first highly efficient liquid hydrogen filling system realizes commercial demonstration of heavy truck hydrogenation [Internet]. 2022 [accessed 2026]. Available from: https://news.bjx.com.cn/html/20220523/1227275.shtml

[62] Hao JF, Qu WQ, Teng LJ. Characteristics and technical research and development difficulties of hydrogen refueling gun in hydrogen refueling station. New Technol New Prod China. 2020; (409): 35-9. http://doi.org/10.13612/j.cnki.cntp.2020.03.017

[63] Liquid hydrogen hydrogenation gun product development iteration documentary [Internet]. 2022 [accessed 2026]. Available from: https://mp.weixin.qq.com/s/tcnBMiZj3XSPWwnKFsd4Mw

[64] Peschka W. Liquid hydrogen pumps for automotive application. Int J Hydrogen Energy. 1990; 15(11): 817-25. http://doi.org/10.1016/0360-3199(90)90018-T

[65] Aceves SM, Berry G, Espinosa-Loza F. LLNL/Linde 875 bar liquid hydrogen pump for high density cryogenic vessel refueling. In: FY 2012 Annual Progress Report, DOE Hydrogen Program; 2012.

[66] Zhan Y. Research and development of cryogenic liquid hydrogen pump [dissertation]. Wuhan: Huazhong University of Science and Technology; 2008.

[67] Li Q, Li Q. Development of submerged liquid hydrogen pump. In: The 11th National Cryogenic Engineering Conference; 2013. p. 335-7.

[68] Wu W, Yang SQ, Xue R. Development status and key technologies of liquid hydrogen piston pump. Vacuum Cryog. 2022; 28(2): 129-35.

[69] Arnold G, Wolf J. Liquid hydrogen for automotive application next generation fuel for FC and ICE vehicles. Teion Kogaku (J Cryog Supercond Soc Jpn). 2005; 40(6): 221-30. http://doi.org/10.2221/jcsj.40.221

[70] Petitpas G, Aceves SM. Liquid hydrogen pump performance and durability testing through repeated cryogenic vessel filling to 700 bar. Int J Hydrogen Energy. 2018; 43(39): 18403-20. http://doi.org/10.1016/j.ijhydene.2018.08.097

[71] Feng SG, Qin DC, Leng QY. Technical research of liquid hydrogen loading arm[J]. Mechanical and Electrical Information, 2021; 671(29): 46-48. DOI:10.19514/j.cnki. cn32-1628/tm.2021.29.018.

[72] Yin B, Qiu H, Dong F, Wang Z, Jia H, Xie X. Study on the pressurization liquid hydrogen supply characteristics in hydrogen fuel cell vehicles. Energy. 2025; 338: 138897. http://doi.org/10.1016/j.energy.2025.138897

[73] Hettinger W, Michel F, Ott P, Theissen F. Refueling equipment for liquid hydrogen vehicles. Int J Hydrogen Energy. 1998; 23(10): 943-7. http://doi.org/10.1016/S0360-3199(97)00137-7

[74] Ku AY, Reddi K, Elgowainy A, McRobie J, Li J. Liquid pump-enabled hydrogen refueling system for medium and heavy duty fuel cell vehicles: station design and technoeconomic assessment. Int J Hydrogen Energy. 2022; 47(61): 25486-98. http://doi.org/10.1016/j.ijhydene.2022.05.283

[75] Li J, Ramteke A, Youn E, Hansen E, Kratschmar K, Prakash A, *et al*. Liquid pump-enabled hydrogen refueling system for heavy duty fuel cell vehicles: pump performance and J2601-compliant fills with precooling. Int J Hydrogen Energy. 2021; 46(42): 22018-29. http://doi.org/10.1016/j.ijhydene.2021.04.043

[76] Zhang ZY, Wang F, Zhao YZ. Review of on-board cryo-hydrogen storage system for automotive. Low Temp Spec Gases. 2020; 38(3): 1-8.

[77] Li Z, Hou J, Markert F. Towards a novel boil-off gas handling system for liquid hydrogen fuel cell vehicles. Int J Hydrogen Energy. 2025; 158: 150544. http://doi.org/10.1016/j.ijhydene.2025.150544

[78] Li Z, Hou J, Markert F. Boil-off gas management for onboard LH2 in hydrogen-powered vehicles. J Phys Conf Ser. 2025; 3084(1): 012048. http://doi.org/10.1088/1742-6596/3084/1/012048

[79] Emans M, Mori D, Krainz G. Analysis of back-gas behaviour of an automotive liquid hydrogen storage system during refilling at the filling station. Int J Hydrogen Energy. 2007; 32(12): 1961-8. http://doi.org/10.1016/j.ijhydene.2006.09.002

[80] Chen Y, Guo L, Yang SQ. Development and prospect of liquid hydrogen zero boil-off storage system. Vacuum Cryog. 2023. [accessed 2023 Aug 24]. Available from: http://kns.cnki.net/kcms/detail/62.1125.O4.20230816.1009.004.html

[81] From the Apollo-era to today, cryogenic tanks hold key to hydrogen economy. (accessed on 2026). Available from: https://www.sierranevadaally.org/2021/07/02/from-the-apollo-era-to-today-cryogenic-tanks-hold-key-to-hydrogen-economy/

[82] Garceau NM, Kim SY, Lim CM, Cho MJ, Kim KY, Baik JH. Performance test of a 6 L liquid hydrogen fuel tank for unmanned aerial vehicles. In: IOP Conference Series: Materials Science and Engineering; 2015; 101(1): 012130. http://doi.org/10.1088/1757-899X/101/1/012130

[83] Zhang ZY, Xie H. Hydrogen utilization - status quo and analysis of liquid hydrogen production, storage and transportation technology. Renew Energy Resour. 2023. http://doi.org/10.13941/j.cnki.21-1469/tk.20220726.001

[84] Xie XJ. Domestic liquid hydrogen technology equipment and industrial application. Sci News. 2022; 24(2): 20-2.

[85] Commission Regulation (EU) No. 406/2010: implementing Regulation (EC) No. 79/2009 on type-approval of hydrogen-powered motor vehicles. Off J Eur Union; 2010 Apr 26 (accessed 2026). Available from: https://www.eea.europa.eu/policy-documents/commission-regulation-eu-no-406-2010

[86] Economic Commission for Europe. Proposal for a global technical regulation on hydrogen and fuel cell vehicles [Internet]. 2013 Apr 12 (accessed 2026). Available from: https://unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a13en.pdf

[87] Chen XL, Liu XM, Wang J. Technology and standardization of liquid hydrogen storage and transportation. Chem Ind Eng Prog. 2021; 40(9): 4806-14. http://doi.org/10.16085/j.issn.1000-6613.2021-0162

[88] Society of Automotive Engineers. Standard for fuel systems in fuel cell and other hydrogen vehicles: SAE J2579-2018. 18 June 2018 (accessed on 2026). Available from: https://www.sae.org/standards/content/j2579_201806

[89] Hydrogen Energy and Fuel Cell Industry Innovation Strategic Alliance in China. White paper on hydrogen energy and fuel cell industry in China [report]. Beijing: People's Daily Press; 2020.

[90] Cui MY, Zhu XP, Xue K. Hydrogen storage technology of hydrogen fuel cell vehicle and its development status. Automob Appl Technol. 2022; 47(10): 173-8. http://doi.org/10.16638/j.cnki.1671-7988.2022.010.036

[91] Zhang ZY, Zhang GQ, Liu YQ. Research status and development direction of on-board hydrogen storage technologies. Oil Gas Storage Transp. 2018; 37(11): 1207-12.

[92] Park YM. Literature research on the production, loading, flow, and heat transfer of slush hydrogen. Int J Hydrogen Energy. 2010; 35(23): 12993-3003. http://doi.org/10.1016/j.ijhydene.2010.04.074

[93] Carney RR, Dwyer RF, Long HM. Theoretical, experimental and analytical examination of subcooled and solid hydrogen [report]. Final Report on Air Force Contract AF33(657)-10248; 1964.

[94] Ohira K. Slush hydrogen production, storage, and transportation. In: Compendium of hydrogen energy. Woodhead Publishing; 2016. p. 53-90. http://doi.org/10.1016/B978-1-78242-362-1.00003-1

[95] Xie FS, Xia SQ, Zhu YH. Visual experimental study on preparation of mixture of liquid hydrogen and solid hydrogen (slush hydrogen). J Xi'an Jiaotong Univ. 2022; 56(6): 26-33.

[96] Xia S, Xie F, Sun Q, Li Y. Numerical study on settlement behaviors of slush hydrogen in cryogenic tank. Asia-Pac J Chem Eng. 2022; 17(3): e2759. http://doi.org/10.1002/apj.2759

[97] Cooperation with Linde 2020. Available from: https://www.daimlertruck.com/en/innovation/powertrain/partnerships

[98] Yang M, Hu S, Yang F, Xu L, Bu Y, Yuan D. On-board liquid hydrogen cold energy utilization system for a heavy-duty fuel cell hybrid truck. World Electr Veh J. 2021; 12(3): 136. http://doi.org/10.3390/wevj12030136

[99] Yang ML. Construction of vehicle hydrogen energy system supply facilities. Automob Parts. 2003; (12): 27-30.

[100] Pu L, Yu HS, Dai MH, He Y, Sun R, Yan T. Research progress and application of high-pressure hydrogen and liquid hydrogen in storage and transportation. Chin Sci Bull. 2022; 67(19): 2172-91. http://doi.org/10.1360/TB-2022-0063