The Study of Hydrogen Energy Storage and Release

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Abstract. This paper delves into the storage and release mechanisms of hydrogen energy, focusing on the liquefaction of hydrogen and fuel cell technologies. It explores the advantages and challenges of liquid hydrogen storage, and it highlights the advantages of this approach, such as its high energy density, making it suitable for long-distance transportation and space-limited applications. However, the study also points out challenges, including evaporation loss. These issues require advanced insulation technologies and improved cycle systems to manage effectively, including its high energy density and issues like evaporation loss and discusses hydrogen fuel cells' efficiency in converting hydrogen into electricity. The study highlights the significance of hydrogen energy in sustainable energy transition and suggests future research directions for optimizing storage and conversion technologies and integrating them with renewable energy systems. The working principle of hydrogen fuel cells involves the electrochemical conversion of hydrogen into electricity, showcasing a clean energy process. The paper also discusses the characteristics of hydrogen production processes, emphasizing their importance in the sustainable energy transition. This research contributes to advancing low-carbon energy solutions and addressing climate change challenges.

Keywords: Hydrogen; liquid hydrogen; storage; release.

1. Introduction

In the quest for sustainable and clean energy solutions, hydrogen has emerged as a pivotal element, offering a path toward a low-carbon future. The storage and release of hydrogen energy are at the forefront of contemporary research, addressing the challenges associated with the transition to renewable energy sources. This paper aims to delve into the intricate mechanisms of hydrogen energy storage and release, highlighting their significance, technological advancements, and the current landscape of research in this field.

Hydrogen, the most abundant element in the universe, holds tremendous potential as a clean energy carrier. Its high energy content per unit mass and zero-emission profile upon combustion or use in fuel cells make it a compelling alternative to fossil fuels. The ability to harness hydrogen energy efficiently is integral to mitigating the escalating concerns of climate change and dwindling fossil fuel reserves. The transition to a hydrogen-based energy economy is poised to revolutionize industries, transportation, and power generation, aligning with global efforts to achieve carbon neutrality.

The storage of hydrogen, however, poses substantial challenges due to its low volumetric energy density and the difficulties in handling the gas safely and efficiently. Various storage methods have been explored, including physical storage under high pressure or low temperatures, and chemical storage through metal hydrides or liquid organic hydrogen carriers. Each method presents its unique trade-offs between energy density, safety, cost, and operational feasibility. The development of advanced materials and technologies for hydrogen storage is critical to maximizing its utility and integration into the existing energy infrastructure.

Equally crucial is the effective release of hydrogen energy. This involves the controlled release of hydrogen from storage and its conversion into usable energy forms, typically electricity. Fuel cells represent a significant technology in this domain, converting hydrogen into electricity through electrochemical reactions, with water being the only byproduct. The efficiency, durability, and cost-effectiveness of fuel cell technologies are central to their adoption and widespread use.

Current research is dynamically evolving, driven by the urgency to find sustainable energy solutions. Innovations in materials science, nanotechnology, and engineering are paving the way for more efficient, safe, and economically viable hydrogen storage and release systems. Research efforts are also focused on integrating hydrogen technologies into renewable energy systems, enhancing the grid's stability and resilience.

In conclusion, the storage and release of hydrogen energy stand at a critical juncture in the transition to a sustainable energy future. This paper seeks to provide a comprehensive overview of the current state of the art, challenges, and future directions in this vital field of research.

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2. Hydrogen Energy Storage

The section discusses the advantages of storing hydrogen in a liquefied form. The section also touches upon the general characteristics of hydrogen, such as its low density and safety aspects.

2.1. Liquefaction Hydrogen Storage

When hydrogen is liquefied before storage, it has the highest energy storage density in terms of volume. Hydrogen can be liquefied at one hundred and fifty degrees Celsius. Cryogenic LPG storage tanks known as cryo-tanks are now capable of high-quality production.

Evaporation loss in the context of liquefied hydrogen storage refers to the loss of hydrogen due to its conversion from liquid to gas. This phenomenon is a key challenge in storing liquid hydrogen, as hydrogen has a very low boiling point (-252.9°C). Even with advanced insulation techniques, some heat will inevitably enter the storage tank, causing a portion of the liquid hydrogen to evaporate. This evaporated hydrogen increases the pressure inside the tank, and if not managed properly, it may be vented to avoid over-pressurization, leading to a loss of stored hydrogen. Managing evaporation loss is crucial for the efficiency and economy of hydrogen storage and transportation systems.

The evaporation loss caused by the continuous heating of liquefied hydrogen in the storage tank can be kept to a minimum. [1] At atmospheric pressure, the melting point of liquid hydrogen is 20k and the latent heat of gasification is 921kj/mol. The density of liquid hydrogen at room temperature and pressure is 845 times that of gaseous hydrogen, and the volume energy density of liquid hydrogen storage is several times higher than that of compressed storage. Liquid hydrogen has a high calorific value, 3 times that of gasoline per kilogram. Liquid hydrogen storage is particularly suitable for transport applications where storage space is limited. The mass of liquid hydrogen storage is minimal and the tank volume is much smaller than that of high-pressure compressed hydrogen storage. In terms of mass and volume, liquefaction storage is an ideal way to store hydrogen [2].

2.2. Characteristics of hydrogen

The density of hydrogen is low, and at 20MPa pressure, its density is 14.4kg/m3. Hydrogen has long been regarded as a dangerous chemical because of its low ignition point, wide explosion limit range and high diffusion coefficient. Hydrogen is the least dense gas known, the specific gravity is much lower than air, the diffusion coefficient is nearly 12 times that of gasoline, is nearly 4 times that of natural gas, and it is easy to diffuse in the air after leakage, making it difficult to form explosive aerosol when hydrogen leaks. Therefore, hydrogen leakage in open space is safe and controllable. The comparison of the properties of hydrogen with gasoline steam and natural gas is shown in Table 1. [3] It can be seen, that Hydrogen is more environmentally friendly and can produce more energy than natural gas

Table 1. Comparison of properties of Hydrogen with gasoline vapor and natural gas [4].

Technical index	Hydrogen	Evaporative emission control	Natural gas
Explosion limits (%)	4.1-75	1.4-7.6	5.3-15
Ignition energy (MJ)	0.02	0.2	0.29
Diffusion coefficient (10 -5m2 /s)	6.11	0.55	1.61
Energy density (MJ/kg)	143	44	42

2.3. Hydrogen Liquefaction Cycle

The hydrogen liquefaction cycle is a process in which hydrogen is converted from a gaseous state to a liquid state and continuously liquefied through a circulation system. Liquid hydrogen has a higher density and can store more hydrogen in a relatively small volume. This liquid form facilitates the transportation of hydrogen energy over long distances between where it is produced and consumed. Through the liquefaction cycle, hydrogen can be produced, stored, and transported when needed to meet the demand for hydrogen in different regions and industries.

In addition, the hydrogen liquefaction cycle provides important technical support for the development of hydrogen energy, making hydrogen energy more convenient and feasible. In short, the hydrogen liquefaction cycle plays an important role in the hydrogen energy industry, which can improve the storage and transportation efficiency of hydrogen and promote the development and application of hydrogen energy. Therefore, this section mainly introduces:1. Linde-Hampson Circulation 2. Claude cycle3.The Claud cycle of liquid nitrogen precooling4.Helium refrigeration cycle

(1) Linde-Hampson Circulation

In 1885, Michael Faraday proposed the theory of gas liquefaction, using ether and dry ice pool cooling, which can reach a cooling temperature of -110 C. At that time, gases with boiling points below this temperature (including hydrogen) could not be liquefied and were called "permanent gases" [5].

In 1895, Carl von Linder and Wilhelm Hampson invented a simple air liquefaction cycle. That's the Linde-Hampson cycle, but this system doesn't get liquid hydrogen. At the same time, Barron [6] also proposed the Linde-Hampson cycle with liquid nitrogen precooling, which could liquefy hydrogen, and conducted experiments. The process flow is shown in Fig.1.

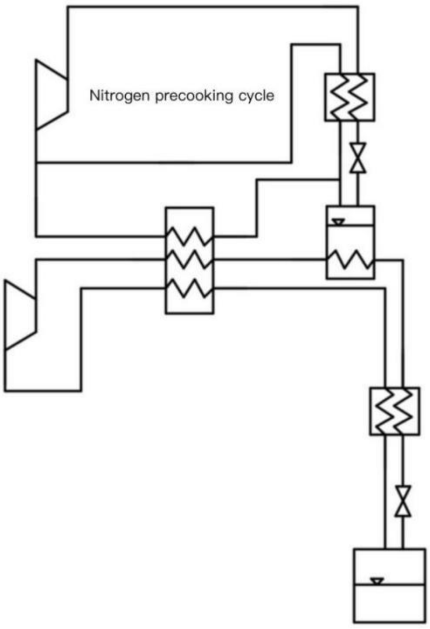

Fig 1. The Linde-Hampson cycle with LN2 Precooling [5].

Fig.1 shows the Linde-Hampson Circulation. Heat Exchangers typically represented by the zigzag lines, are devices that allow heat transfer from the gas to the cooling medium, which could be another gas or liquid. The triangle usually increases the pressure of the gas, raising its temperature as part of the refrigeration cycle.

Expansion Valve is shown as a valve symbol and reduces the pressure of the gas, causing it to cool rapidly. This is part of the Joule-Thomson effect which is used in refrigeration cycles.

As indicated in the schematic, would be used to pre-cool the gas using liquid nitrogen before it is further cooled, which improves the efficiency of the cycle.

Each part of the cycle contributes to the overall process of cooling and liquefying the gas. In a complete and functioning system, these components would be connected to additional valves, sensors, and storage tanks to manage the flow and storage of the cryogenic liquid

In 1898, James Duvall achieved the first liquefaction of hydrogen [7]. The process uses phenol and liquid air to pre-cool hydrogen at a pressure of 18MPa, which is similar to Linde's system for air liquefaction.

(2) Claude cycle

In 1902, Georges Claude [8] invented the Claude cycle, which, in addition to liquefying air, can also be used to liquefy hydrogen. In addition to a throttle valve, a hydrogen expander was used in the Claude cycle, which produced temperatures much lower than those produced by the medium enthalpy expansion of the Linde-Hampson cycle.

(3) The Claud cycle of liquid nitrogen precooling

Timmerhaus and Flynn argued that if pre-cooling with liquid nitrogen was applied, the energy efficiency would be higher than that of pre-cooled Linde.

The Hampson cycle can be improved by 50% to 70% [9]. Nandi and Sarangi compared the two cycles and proposed that the Claude cycle is the basis of most gas liquefaction cycles [10]. The Ingolstadt plant, built in 1992 near Munich, Germany, utilizes an improved cloud cycle with precooling [8].

(4) Helium refrigeration cycle

Nandi, Sarangi [10], and Barron [7] have all suggested that hydrogen liquefaction could also be assisted by helium chillers, but this cycle has not yet been applied to large-scale hydrogen liquefaction plants.

The hydrogen liquefaction cycle of helium refrigeration is divided into two parts: the hydrogen liquefaction cycle and the refrigeration cycle using helium as the refrigerant. The independent helium refrigeration cycle belongs to the improved Claude cycle, and its process flow is shown in Fig. 2. After being compressed by the compressor and pre-cooled by liquid nitrogen, helium enters the expansion machine to expand and cool down. In this process, helium is always in a gas state and will not be liquefied, but it can reach the temperature below the boiling point of hydrogen to liquefy hydrogen. In the hydrogen liquefaction process, the high-pressure hydrogen compressed by a compressor is first pre-cooled by liquid nitrogen, then cooled by low temperature helium refrigerant in a heat exchanger, and finally liquefied by throttling expansion.

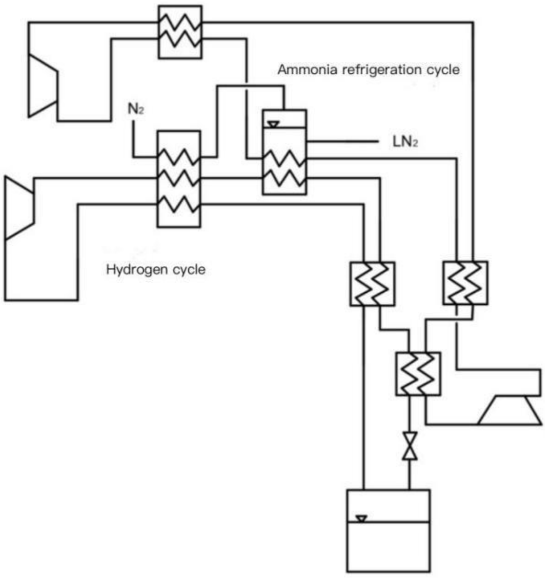

Fig 2. The hydrogen liquefaction cycle with the cooling [7].

3. Liquid Nitrogen Precooling - Helium Expansion Refrigeration Process Simulation

Liquid energy is more stable than gas energy in our energy storage state, so we can make hydrogen energy better stored in new energy

The process simulation model of the liquid nitrogen precooling and helium expansion refrigeration process is shown in Fig.3. The raw hydrogen is converted by a five-stage heat exchanger and a four-stage positive and secondary hydrogen dispersion at constant temperature. The positive and secondary hydrogen conversion is achieved in the model by a conversion reactor, and the conversion reaction from standard hydrogen to secondary hydrogen occurs at constant temperature.

The obtained liquid hydrogen product parameters are 300kPa pressure and 20.00K temperature, and the liquefaction rate of the process is 100%. The circulating helium flow rate is 1505kg/h, and the circulating nitrogen flow rate is 900kg/h [3].

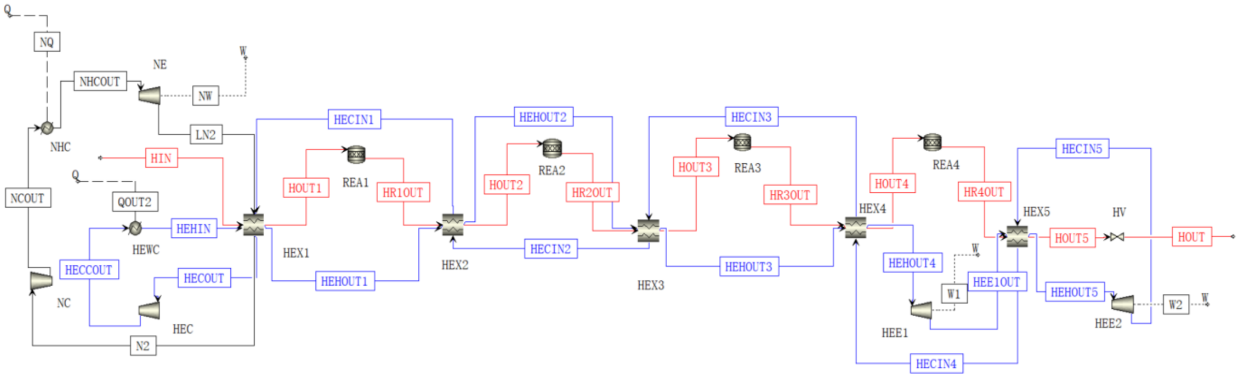

Fig 3. Process model of LN2 Precooling and He Expansion cooling [3].

3.1. Simulation of Liquid Nitrogen Precooling and Hydrogen Independent Expansion Refrigeration Process

The process simulation model of liquid nitrogen precooling and hydrogen independent expansion refrigeration process is shown in Fig. 4. After the raw hydrogen goes through the compressor and water cooler, it enters the pre-cooling and refrigeration link, passes through the four-stage heat exchanger and the three-stage positive and secondary hydrogen dispersion constant temperature transformation, and finally completes the liquefaction through throttling expansion.

The product parameters of liquid hydrogen are 300kPa pressure, 24.40K temperature, and the process liquefaction rate is 17.72%. The circulating hydrogen flow rate is 1505kg/h, and the circulating nitrogen flow rate is 900kg/h. [3].

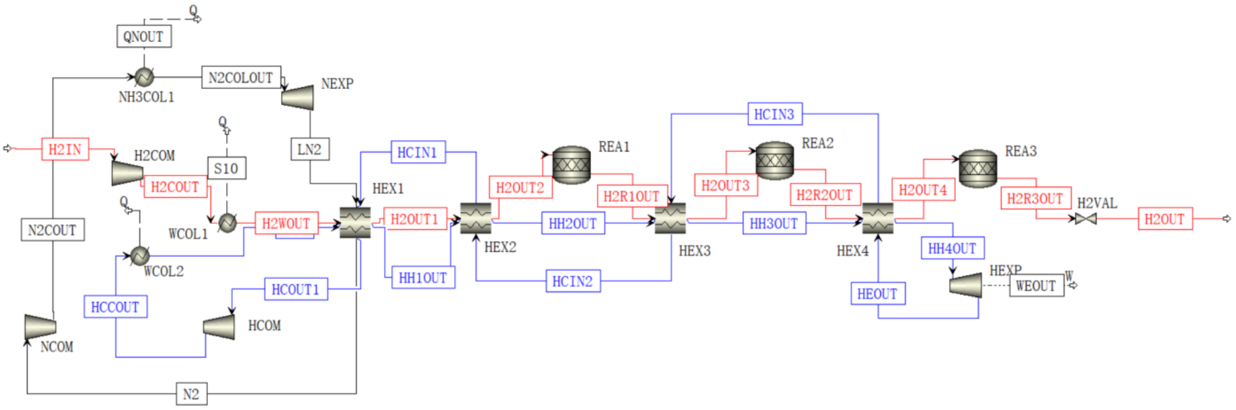

Fig 4. Process model of LN2 Precooling and H2 independent Expansion cooling [3].

3.2. Simulation of Liquid Nitrogen Precooling And Hydrogen Shunt Expansion Refrigeration Process

The process simulation model of the liquid nitrogen precooling and hydrogen shunt expansion refrigeration process is shown in Fig. 5. The raw gas enters the pre-cooling process after passing through the compressor and water cooler, and then carries out two separate flow refrigeration and two positive and secondary hydrogen conversion reactions, and finally completes the liquefaction through throttling expansion.

The product parameters of liquid hydrogen are 300kPa pressure, 24.40K temperature, and the process liquefaction rate is 8.38%. The circulating nitrogen flow rate is 900kg/h [3].

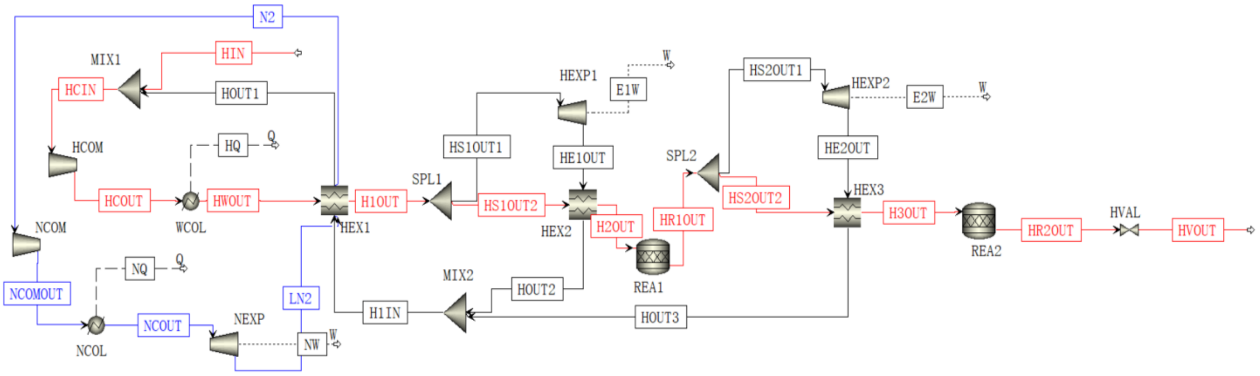

Fig 5. Process model of LN2 Precooling and H2 split Expansion cooling [3].

4. The Working Principle of a Hydrogen Fuel Cell

At present, according to the existing technology and market demand, there are many types of hydrogen fuel cells, mainly profit Hydrogen is used to undergo different chemical reactions through a variety of different chemical materials, in which the hydrogen is stimulated. The chemical produces electricity. Hydrogen fuel cells are divided into many kinds due to different materials, the most common one A Proton Exchange Membrane Hydrogen Fuel Cell (PEMFC) is a proton exchange membrane hydrogen fuel cell (PEMFC), based on which the design and research were carried out.

Hydrogen is passed into the fuel cell through the anode with the constant movement of the gas, hydrogen diffuses to the anode diffusion layer, and the anode diffusion layer has a catalyst, Converting hydrogen into hydrogen ions. Similarly, the cathode is connected with oxygen and diffused into the cathode diffusion layer and the cathode catalytic layer Containing a catalyst to catalyze the REDOX reaction.

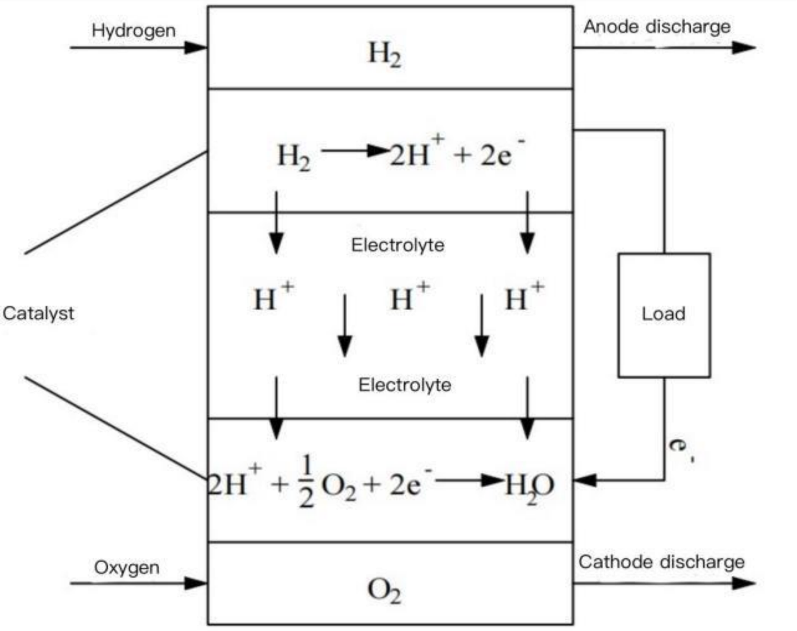

Fig 6. Hydrogen fuel cell structure diagram [3].

As can be seen from Fig. 6, the working process of hydrogen fuel cells can be understood as the reverse process of electrolysis of water. That is both hydrogen and oxygen are converted into ions, and then hydrogen ions and oxygen ions are combined to produce water and electricity.

In hydrogen fuel cells, hydrogen gas is injected into the interior through the anode of the hydrogen fuel cell, due to hydrogen is a gas that can slowly diffuse, and finally as a gas hydrogen comes to the diffusion layer and acts as a catalyst. It then oxidizes to H+ [11,12]. Hydrogen becomes H+ by oxidation and loses electrons, electrons it passes through an external circuit to the cathode of the hydrogen fuel cell, and electricity is generated during the movement of the electrons flow, which provides electrical energy for subsequent load units; The anodic oxidation product H+ is in the hydrogen fuel cell the part crosses the proton exchange membrane and then reaches the cathode of the hydrogen fuel cell where it reacts further with oxygen ions yes.

The cathode of the hydrogen fuel cell acts as the oxygen injection end, and the oxygen is injected into the hydrogen fuel cell from the cathode. The oxygen is constantly moving inside the hydrogen fuel cell, and the oxygen diffuses through the diffusion movement to the catalyst. The cathode diffusion layer is catalyzed into oxygen ions. When H+ diffuses from the anode to the cathode, it combines electrons from the outside and reacts with oxygen ions to produce water, the cathode of a hydrogen fuel cell.

The reverse process of electrolysis of water, that is, the combination of hydrogen ions and oxygen ions to form water, can be regarded as hydrogen combustion the essence of the battery power generation, in the whole process of chemical reaction, there is only a little exothermic reaction in the combination reaction. Therefore, very little energy is lost in the form of heat, and most chemical energy is converted to electrical energy, and the only product of the reaction is water, and the generated water can also be used for recycling hydrogen production, clean and environmentally friendly.

5. Conclusion

This paper focuses on the storage and release mechanism of hydrogen energy. The paper discusses in detail the methods of liquefied hydrogen storage, including the advantages, challenges, and related technologies such as the Linde-Hampson cycle and the Claude cycle. At the same time, the paper also covers the working principle of hydrogen fuel cells and emphasizes the importance of hydrogen energy in the sustainable energy transition.

The study found that liquefied hydrogen storage has a high energy density and is suitable for long-distance transportation and space-limited applications. Although there are challenges, such as evaporation losses, these can be managed effectively with advanced insulation technology and improved circulation systems. Hydrogen fuel cell technology, as an important way of hydrogen energy release, converts hydrogen energy into electricity efficiently through electrochemical reactions.

Going forward, the research could also further explore the optimization of hydrogen storage and conversion technologies, as well as their integration with renewable energy systems. The development of hydrogen energy has far-reaching significance for realizing low-carbon energy transition and tackling climate change. Through continuous technological innovation and research, hydrogen energy has the potential to become a key component of clean energy.

References

[1] Zhou X F. Green energy -- Introduction of hydrogen storage methods [J]. World Science,2006(9):25-26.

[2] Sheng Xuilian. Research on hydrogen energy storage development and liquid hydrogen storage container technology [J]. Science & Technology Economic Market,2010(7):21-22

[3] Wei Xiaowen. Claude cycle-based hydrogen liquefaction process simulation study [D]. China university of petroleum (Beijing), 2023. The DOI: 10.27643 /, dc nki. Gsybu. 2021.000291.

[4] China Hydrogen Energy Alliance. China Hydrogen Energy and Fuel Cell Industry White Paper [M]. 2019(06).

[5] Foerg W. History of cryogenics: the epoch of the pioneers from the beginning to the year 1911. Int J Refrig 2002; 25(3): 283-92.

[6] Dewar J. Liquid hydrogen. Science 2018; 8(183): 3-6

[7] Barron R F. Cryogenic systems. Oxford, United Kingdom: Oxford University Press; 1966.

[8] Bracha M, Lorenz GA, Wanner M. Large-scale hydrogen liquefaction in Germany. Int J Hydrogen Energy 1994; 19(1):53-9.

[9] Timmerhaus K D, Flynn T M. Cryogenic process engineering. New York: Springer; 1989.

[10] Nandi T K, Sarangi S. Performance and optimization of hydrogen liquefaction cycles. Int J Hydrogen Energy 1993; 18(2): 131-9.

[11] Wei Xiaowen. Claude cycle-based hydrogen liquefaction process simulation study [D]. China university of petroleum (Beijing), 2023. The DOI: 10.27643 /, dc nki. Gsybu. 2021.000291.

[12] Yang Bo, Ge Qiongxuan, Zhao Lu, et al. Optimization of Return Power Characteristics of Bidirectional Full-bridge series resonant DC/DC Converter [J]. Proceedings of the CSEE, 2019, 39(23): 6990-6999.