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Research Article

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Research Status and Consequence Analysis of Leakage and Diffusion of Liquid Hydrogen

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Abstract: As an efficient and clean energy carrier, liquid hydrogen has been widely utilized in production, storage, and transportation technologies. However, due to its extremely low boiling point and high volatility, liquid hydrogen poses significant leakage risks during its production, storage, and utilization, making its safety a growing concern. This study systematically reviews the technologies related to liquid hydrogen production, storage, and transportation, with a particular focus on the current research status of liquid hydrogen leakage and dispersion. The dispersion mechanisms and influencing factors under different environmental conditions are thoroughly analyzed. Furthermore, potential safety hazards and consequences associated with liquid hydrogen leakage, such as cryogenic damage, hydrogen cloud formation, and explosion risks, are summarized. Based on these findings, key directions for future research on liquid hydrogen leakage prevention and safety measures are proposed to provide theoretical support and technical guidance for the safe utilization of liquid hydrogen.

Keywords: Hydrogen energy; Liquid hydrogen; Hydrogen safety

1. Introduction

The global energy sector is currently facing numerous challenges, including energy structure adjustments and security of supply [1]. As a high energy density, non-toxic, and pollution-free energy carrier, hydrogen is regarded as a key pathway toward achieving zero-carbon emissions. In recent years, significant advancements have been made in hydrogen technology, and the application of liquid hydrogen has been expanding in fields such as aerospace, transportation, and energy storage [2]. Many countries have incorporated hydrogen into their long-term energy development strategies, while major international energy companies are actively investing resources to accelerate the growth of the hydrogen industry. Against this backdrop, the safety of liquid hydrogen has emerged as a critical research focus, particularly in its production, storage, and transportation processes. Due to its extremely low boiling point and high volatility, the leakage and dispersion characteristics of liquid hydrogen are of paramount importance [3]. Therefore, an in-depth investigation into the mechanisms of liquid hydrogen leakage and dispersion, as well as the development of effective prevention and control measures, is essential for ensuring its safe and efficient utilization.

As a current industrial raw material and a potential major energy carrier in the future, the industrial development of hydrogen energy faces many related issues, particularly the bottleneck problems of large-scale, low-cost production and long-distance transportation in the application process. Currently, the main methods of industrial hydrogen storage include high-pressure hydrogen storage, cryogenic liquid hydrogen storage, metal hydride hydrogen storage, organic liquid hydrogen storage, liquid ammonia hydrogen storage, and underground hydrogen storage. Liquid hydrogen storage is one of the most common hydrogen storage methods today. Compared to high-pressure storage and transportation, liquid hydrogen storage and transportation have advantages such as lower transportation costs, higher hydrogen purity, and easier measurement, making it more suitable for large-scale deployment and transportation.

Similar to gaseous hydrogen storage technology, liquid hydrogen storage technology also faces leakage risks, and due to the large leakage volume per unit time, once leakage occurs, it can cause significant disasters. With the increasing use of hydrogen energy, conducting research on the safety of liquid hydrogen has become an urgent task, which has important practical significance for the safe use and management of hydrogen.

2. Production, Storage, And Transportation of Liquid Hydrogen

Hydrogen Liquefaction

Liquid hydrogen is the most effective method for achieving the highest hydrogen storage density, but the process of obtaining liquid hydrogen involves high technical barriers. When producing liquid hydrogen on a large scale, it is necessary to consider its energy consumption and efficiency.

The liquefaction of hydrogen was first achieved by James Dewar in the UK in 1898 through the J-T throttling process. By 1902, the Claude cycle emerged, differing from previous hydrogen liquefaction methods mainly in the use of an expansion machine. The Claude cycle, which uses liquid nitrogen pre-cooling and an expansion machine to provide low-temperature cooling, is about 50-70% more efficient than the Linde-Hampson cycle using J-T throttling.

Currently, the commonly used hydrogen liquefaction processes can be divided into the simple Linde-Hampson method, which uses the Joule-Thompson effect for throttling expansion, and the adiabatic expansion method, which combines a turbine expansion machine for cooling. In actual production, depending on the scale of liquid hydrogen production, the adiabatic expansion method can be further divided into the reverse Brayton method, which uses helium as a medium for expansion refrigeration to produce low temperatures and cool high-pressure gaseous hydrogen to liquid, and the Claude method, which allows hydrogen to adiabatically expand and cool itself.

Liquid Hydrogen Storage and Transportation

Cryogenic liquid hydrogen storage is a physical storage method that compresses hydrogen and cools it to -253°C to form liquid hydrogen, which is then stored in specially designed cryogenic containers. The advantage of cryogenic liquid hydrogen storage is its high density, reaching 70.78 kg/m3, which is about 850 times the density of hydrogen under standard conditions. Even in high-pressure hydrogen storage, for example, at 90 MPa, the volumetric density is only 60% of that of liquid hydrogen, far lower than the volumetric storage density of liquid hydrogen.

Liquid hydrogen storage and transportation can be divided into two categories: container storage and transportation, and pipeline transportation. Container storage and transportation typically use spherical and cylindrical tanks. For transportation, liquid hydrogen trailers, liquid hydrogen rail tankers, and liquid hydrogen tankers are used.

In addition to considering factors such as impact and vibration during conventional liquid transportation, due to the low boiling point of liquid hydrogen (20.3 K), small latent heat of vaporization, and easy evaporation, strict technical measures to reduce heat leakage or lossless transportation methods must be used to minimize or eliminate the vaporization of liquid hydrogen. Otherwise, it can cause tank pressure rise, leading to overpressure risks or venting losses. From a technical perspective, liquid hydrogen storage and transportation mainly use passive insulation techniques to reduce heat conduction and active cooling techniques to reduce heat leakage or generate additional cooling capacity.

3. Liquid Hydrogen Leakage and Diffusion

Main Forms of Liquid Hydrogen Leakage

During the storage, transportation, and use of liquid hydrogen storage tanks, due to factors such as safety valve failure, mechanical damage (including tank material defects, material fatigue, corrosion, and failure or strength reduction at edges and welds), thermal stress, pressure stress, improper operation, or flame impingement causing tank material strength reduction, the tank may experience varying degrees of rupture. Additionally, manganese steel, nickel steel, and other high-strength steels are prone to hydrogen embrittlement. These steels, when exposed to hydrogen for long periods, especially under high temperature and pressure, can significantly lose strength, leading to failure. Therefore, improper material selection for hydrogen contact can result in hydrogen leakage and fuel pipeline failure. Since hydrogen is the lightest element, it is more likely to leak through small holes compared to liquid fuels and other gaseous fuels. Thus, after tank failure, different forms of disasters can occur under different environmental conditions.

Current research on liquid hydrogen leakage can be broadly divided into three directions: liquid hydrogen leakage conditions, environmental factors affecting liquid hydrogen leakage, and potential hazards caused by liquid hydrogen leakage. Due to the limitations of liquid hydrogen properties, numerical simulation methods are mainly used to study liquid hydrogen leakage conditions and environmental factors affecting liquid hydrogen leakage. In experimental research, NASA, the UK Health and Safety Laboratory (HSL), and the German Federal Institute for Materials Research and Testing (BAM) have conducted large-scale experimental studies, obtaining quantitative data describing the motion characteristics of hydrogen clouds formed by liquid hydrogen leakage and diffusion. Subsequent research has often used the results from these three laboratories as reference for validation.

Research Status on Liquid Hydrogen Leakage and Diffusion

Liquid hydrogen is highly diffusive, flammable, and explosive, with a low ignition energy, making it a fuel with a high energy density value. It is prone to accidents during storage, transportation, and refueling, making the study of liquid hydrogen leakage and diffusion. The leakage and diffusion of liquid hydrogen in open spaces can be roughly divided into the following processes [4]: a) Flash evaporation stage. At the beginning of the leakage, part of the liquid hydrogen turns into vapor. b) Heavy gas diffusion stage. The low-temperature liquid hydrogen rapidly exchanges heat with the air and ground, evaporating to form extremely low-temperature gas. The cloud rises from the ground to a higher altitude, with the upper part of the cloud floating upward, forming a certain angle with the downwind direction on the ground. c) Buoyant diffusion stage. After the liquid hydrogen stops leaking, the H concentration drops sharply in a short time, and the tail of the H cloud rises to a certain height. The buoyant diffusion stage is the main stage in the diffusion process of the H cloud. d) Passive diffusion stage. In this stage, the cloud floats in the air due to the balance of gravity and buoyancy, and the concentration slowly decreases under the influence of wind.

Currently, HSL and NASA have conducted large-scale liquid hydrogen leakage experiments. In 2000, STATHARAS JC et al. [5] used the ADREA-HF three-dimensional finite volume code to simulate the German Federal Institute for Materials Research and Testing's experiments on accidental liquid hydrogen leakage between buildings, revealing the significant impact of ground heating on liquid hydrogen diffusion and showing that ground-plume thermal interaction is a major factor in liquid hydrogen release. Subsequently, domestic scholars have also conducted research based on NASA's studies, revealing the diffusion process of combustible clouds under heterogeneous mixing models in open spaces and the impact of spatial constraints (different obstacle positions and whether obstacles are present) on liquid hydrogen leakage and diffusion. LIU Y et al. [6] used the commercial software Fluent to numerically simulate liquid hydrogen leakage, validating NASA's experimental data and analyzing the dilution of H vapor clouds under different spill volumes, spill rates, and outlet liquid mass fractions.

At the same time, domestic and foreign scholars have done a lot of research. VERFONDERN K et al.[4] used the ADREA-HF program to perform CFD (Computational Fluid Dynamics) simulations of NASA's spill experiments. Fan Shuangyu et al. used the ALOHA software to derive the diffusion patterns under different wind speeds, temperatures, and leakage volumes, verifying the accuracy of the ALOHA software within the error range. Wu Mengxi et al. used the commercial software Fluent with the Mixture model as the multiphase flow model, comparing it with NASA experiments to study the leakage characteristics, vaporization process, and cloud formation of liquid hydrogen, exploring the impact of different factors on large-scale liquid hydrogen leakage and diffusion, and providing guidance for risk prevention. MIDDHA et al. [7] used the FLACS software to build a risk assessment model for liquid hydrogen leakage, studying the diffusion and evaporation characteristics of liquid hydrogen and the impact of atmospheric stability on H plume diffusion. Jakel C et al. [8] used the ANSYS-CFX software to illustrate that boundary conditions are more meaningful for small-scale liquid hydrogen leakage experimental validation. Sandia National Laboratory studied high-pressure liquid hydrogen release and proposed a model for calculating the hydrogen dilution distance in liquid hydrogen storage spaces. Numerical simulations of leakage were conducted, validating NASA's experimental data and analyzing the dilution of H vapor clouds under different spill volumes, spill rates, and outlet liquid mass fractions.

Domestic scholars have also conducted research on liquid hydrogen leakage and diffusion in confined spaces. Chen Hui et al. built a liquid hydrogen storage tank model and used UDF (User-defined Function) and CFD to explore the impact of leakage location, source pressure, wind direction, and other factors on liquid hydrogen leakage and diffusion, providing a basis for accident prevention in liquid hydrogen storage at rocket launch sites. Zhao Kang et al. studied the impact of wind speed, leakage speed, and ground temperature on liquid hydrogen leakage in confined spaces. TANG X et al. [9] studied the evaporation and diffusion process of liquid hydrogen in open spaces, garages, and tunnels, providing valuable safety recommendations for solving practical problems.

Current research is mostly based on large-scale leakage experiments. Foreign research combines experimental and numerical simulation methods, while domestic research currently has almost no experimental studies on the liquid hydrogen leakage and vaporization process, mostly relying on numerical simulations. Additionally, there is limited research on the impact of various physical factors during the flash evaporation process under non-ideal conditions.

Consequences of Liquid Hydrogen Leakage Accidents

Operational errors, material failure, design defects, component abnormalities or malfunctions, as well as external collisions and impacts, can cause the rupture and failure of liquid hydrogen storage tanks or pipelines [10]. At the same time, hydrogen's relative molecular mass is smaller than other common fuels, and its diffusion coefficient is about 4 times that of natural gas and 12 times that of gasoline, making it more prone to leakage compared to other substances. After liquid hydrogen leaks, it exchanges heat with the surrounding environment and evaporates, mixing with air to form a low-temperature hydrogen cloud. In 2010, the launch of the Space Shuttle Discovery was delayed due to a hydrogen leak. Historically, the Fukushima nuclear power plant hydrogen explosion accident (2011) also caused significant losses to life and property. The hazards of liquid hydrogen leakage mainly include:

1) Cryogenic injury. Liquid hydrogen is an extremely low-temperature fluid, with a temperature of only about 20 K, which can freeze human tissue. Low temperatures can also alter the physical properties of materials, causing them to fail.
2) Asphyxiation. After liquid hydrogen leaks, it rapidly evaporates and expands, causing a local drop in oxygen concentration. When the oxygen concentration drops to 19%, human activity begins to decline; if the oxygen concentration falls below 10%, consciousness is lost, and death can occur.
3) Chemical explosion. Hydrogen has a low ignition energy, with a minimum ignition energy of only 0.02 mJ, and can spontaneously ignite. At room temperature, its combustion limit in air is wide (hydrogen volume fraction 4-75%). At the same time, a deflagration can occur at relatively low hydrogen concentrations (hydrogen volume fraction 4-8%), with the pressure wave from hydrogen combustion propagating at subsonic speeds. The most severe hazard is detonation (hydrogen volume fraction 18.3-59%), where the explosion propagates at supersonic speeds.
4) Physical explosion. A physical explosion involving rapid and violent expansion of fluid without chemical reactions can also produce explosive shock waves. The most common physical explosion is caused by a boiling liquid expanding vapor explosion (BLEVE) in pressure vessels. The greater the liquid density, the more destructive the BLEVE. If the liquid is flammable, a fireball can be produced. Boiling liquid, expanding vapor, etc., cause pressure spikes in BLEVE. Depending on the energy released by the physical explosion, explosion fragments can cause casualties within a certain range, and the damage increases with the liquid temperature.

4. Conclusion and Outlook

Liquid hydrogen safety is an important guarantee for liquid hydrogen production and utilization, and leakage is a significant factor affecting liquid hydrogen storage and transportation safety. Currently, domestic and foreign scholars' research on liquid hydrogen leakage and diffusion behavior in open and confined spaces is mostly based on numerical simulations. Corresponding liquid hydrogen leakage laboratories should be established to conduct small-scale liquid hydrogen leakage experiments, providing data support for numerical simulation results. Research results show that after liquid hydrogen leaks, it rapidly absorbs heat from the surrounding environment and evaporates into a combustible hydrogen cloud, which is prone to burn and explode when encountering open flames or static electricity. Leakage location, leakage pressure, leakage temperature, leakage flow rate, and environmental factors all affect liquid hydrogen leakage and diffusion. Therefore, it is necessary to comprehensively consider the impact of multiple factors working together. Additionally, when liquid hydrogen leaks, corresponding protective measures can be taken to reduce hazards, and experimental research can be conducted to provide support for the safety prevention of liquid hydrogen leakage.

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