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Overview of the Risk Assessments for Hydrogen Refuelling Stations in Japan

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Hydrogen refuelling stations (HRSs) have attracted widespread attention in Japan. The Ministry of Economy, Trade, and Industry in Japan set a goal for the construction of HRSs in a strategic roadmap. Owing to the explosive and fire hazards associated with HRSs, a considerable amount of safety studies for HRSs has been conducted for several years; however, the safety studies conducted in Japan are yet to be reviewed. This study aimed to comprehensively review the safety studies conducted in Japan, particularly the risk assessment (RA) of HRSs, and to provide useful insights on the direction of future studies on the safety of HRSs. To this end, a comprehensive review of international and Japanese safety studies for HRSs was presented by adopting a bibliometric analysis approach and an overview of Japanese safety studies for HRSs was presented based on the type of HRSs. The results revealed that it is essential to conduct the RA of HRSs, particularly for HRSs yet to be assessed, to contribute to the decision-making process for the social implementation of HRSs in the future.

1. Introduction

In Japan, hydrogen is considered as a required secondary energy for reducing carbon emissions and to achieve carbon neutrality in 2050. Accordingly, the Ministry of Economy, Trade, and Industry, Japan designed and revised a strategic roadmap to achieve a 'Hydrogen society' (METI, 2019). Currently, hydrogen refuelling stations (HRSs) have attracted widespread attention in Japan, and some numerical targets of the roadmap include the construction of 320 and 900 HRSs by 2025 and 2030, respectively. However, owing to hydrogen hazards, such as hydrogen embrittlement, explosiveness, and flammability, HRSs are susceptible to accidents, which have been reported in accident databases (Galassi et al., 2012). Therefore, to achieve the 'Hydrogen society' goal, it is essential to guarantee the safety of the hydrogen infrastructure, including HRS. Accordingly, a considerable amount of safety studies for HRSs have been conducted for several years; however, compared to those of other countries, there has been no review on the safety studies conducted in Japan. Therefore, this study aimed to comprehensively review the safety studies conducted in Japan, particularly, risk assessment (RA) studies, and to provide useful insights on the required direction of future studies on the safety of HRSs. First, international and Japanese safety studies for HRSs were comprehensively reviewed using a bibliometric analysis approach to reveal the institutions that have mainly participated in the safety studies and to clarify the research domains of Japan. Next, an overview of the RAs that has been conducted in Japan was presented based on the type of HRSs. Lastly, the strength of Japan and the required direction of future studies on the safety of HRSs for the implementation of HRSs were discussed.

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2. Bibliometric review of safety studies on HRSs

2.1 International safety studies

A comprehensive review of international safety studies for HRSs was presented to determine the institutions that have mainly participated in the safety studies in recent years. In this study, the VOSviewer, which is a freely available computer program developed for constructing and viewing bibliometric maps (van Eck and Waltman, 2010), was employed to visualize the bibliometric data and to analyse the relationships among authors, institutions, and countries of publications related to the safety studies of HRSs. The data used in this study were retrieved from the Web of Science Core Collection, which is a comprehensive database of articles and includes detailed bibliographic information, on November 14, 2021. The publications were collected through the research topic using 'hydrogen AND station AND safety' or 'hydrogen AND station AND risk' as the search topics, indicating that this term was identified in the Title, Abstract, and Keywords of the publications. The final datasets consisted of 189 publications by 200 authors from 36 countries, and these publications were published in some Journals, namely, International Journal of Hydrogen Energy, Journal of Loss Prevention in the Process Industries, Energies, Sustainability, Energy Policy, Process Safety and Environmental Protection, and Journal of Cleaner Production (except for publications on nuclear energy).A total of 189 publications related to the safety studies of HRSs were observed in the database. Bibliographic data can be used to construct networks, such as co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links. To further understand the institutional distribution of the publications and the relationships of the safety studies among the institutions, the distribution of each publication was presented in a bibliographic coupling network, as shown in Figure 1. The circle areas in the Figure 1 represents the number of publications, the colour of the circles represents the year of publication, and the bibliographic coupling link represents the link between two institutions that cite the same document. In descending order of their number of publications, the institutions that have mainly published articles relating to the safety studies of HRSs include Yokohama National University (YNU), Japan; Tongji University, China; University of Pisa, Italy; Sandia National Laboratories, United States of America; the National Institute of Advanced Industrial Science and Technology (AIST), Japan; and other institutions (Figure 1). Early bibliometric studies around 2012 were mainly published by the University of Pisa, and studies between 2013 and 2014 were mainly published by Tongji University. In addition, studies around 2016 were mainly conducted by Sandia National Laboratories and AIST. Recent studies (after 2018) on the safety of HRS were mainly conducted by YNU. Furthermore, China University of Petroleum, China; Air Liquide, France; and Hiroshima University, Japan, have conducted very recent studies on the safety of HRSs. In addition, the safety studies conducted by most of the institutions have similar research background owing to the relationship between these institutions. These results indicate that Japan has actively conducted safety studies for HRSs and achieved results, as the papers were published recently and the ranks of the number of published references of institutions in Japan were first and fifth.

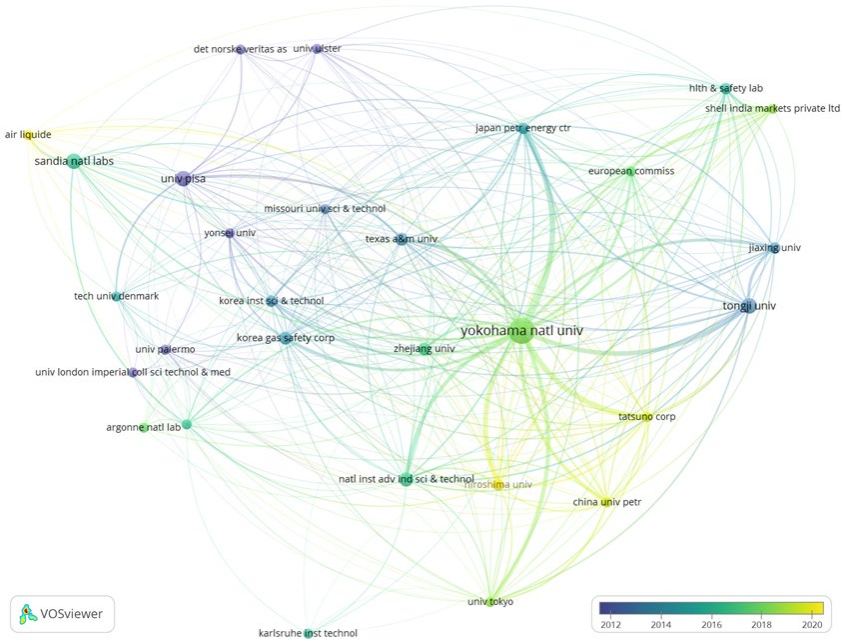

Figure 1 Bibliographic coupling network of the institutions of the publications on the safety studies of hydrogen refuelling station using VOSviewer

2.2 Japanese safety studies

A comprehensive review of the safety studies on HRSs that have been conducted in Japan was presented to clarify the research domains of Japan. For this review, KH Coder (Ver. 3) was utilized to identify the keywords associated with the safety studies on HRSs conducted in Japan. The KH Coder is a freely available computer software developed for quantitative content analysis or text mining (Higuchi, 2021), and it can analyse text data in Catalan, Chinese (simplified), Dutch, English, French, German, Italian, Japanese, Korean, Portuguese, Russian, Slovenian, and Spanish. The data used in the present study were retrieved from the abstracts of research published from New Energy and industrial technology Development Organization (NEDO), which is the main funding source for research on the hydrogen policy of Japan for over 20 years. The publications were collected through the research topic using 'hydrogen AND safety' as the search topics, indicating that this term was identified in the Title and Abstract of the publications.

A total of 97 publications related to HRS safety were observed in the database. Subsequently, a co-occurrence analysis was conducted to identify the intellectual structure of the 97 publications. To further understand the research domain of the safety studies for HRSs, the number of times a research term appeared in the publications and the relationships between these terms are presented in the network in Figure 2. The circled area in the image represents the number of times a term appeared in the publications, the colour of the circles represents the subgraph of the terms, and the network link represents the link between two terms that exhibit a strong relationship. As shown in Figure 2, the yellow cluster (02), which is the core of this network, was mainly comprised of terms, such as 'hydrogen', 'development', and 'pressure'. Further, some communities were comprised of relatively high-frequency nodes of certain keywords. For example, the green cluster (01) was mainly comprised of terms, such as 'material', 'storage', and 'temperature'; the red cluster (04) was mainly comprised of terms, such as 'gas' and 'test'; the blue cluster (05) was mainly comprised of 'catalyst' and 'membrane'; and the orange cluster (06) was mainly comprised of 'project'. In addition, the purple cluster (03) exhibited relatively high-frequency nodes of some key words, such as 'safety', 'station', 'vehicle', and 'standard'. These results indicate that the safety studies for HRSs in Japan focused on studies relating to the standard of HRSs.

3. An overview of risk assessments for HRSs in Japan

As previously mentioned, a considerable amount of safety studies on HRSs have been conducted in Japan. An overview analysis of peer-reviewed articles written by Japanese organizations was conducted. The research and development work of the World energy network (WE-NET) project, which is administrated by NEDO, started in 1993 (Hijikata, 2002). WE-NET aims to establish technologies to construct a renewable energy-based hydrogen energy network. This project has two objectives related to the safety measures and assessment for hydrogen technology: 'Study on the safety design standards' and 'Establishment of safety evaluation method'.

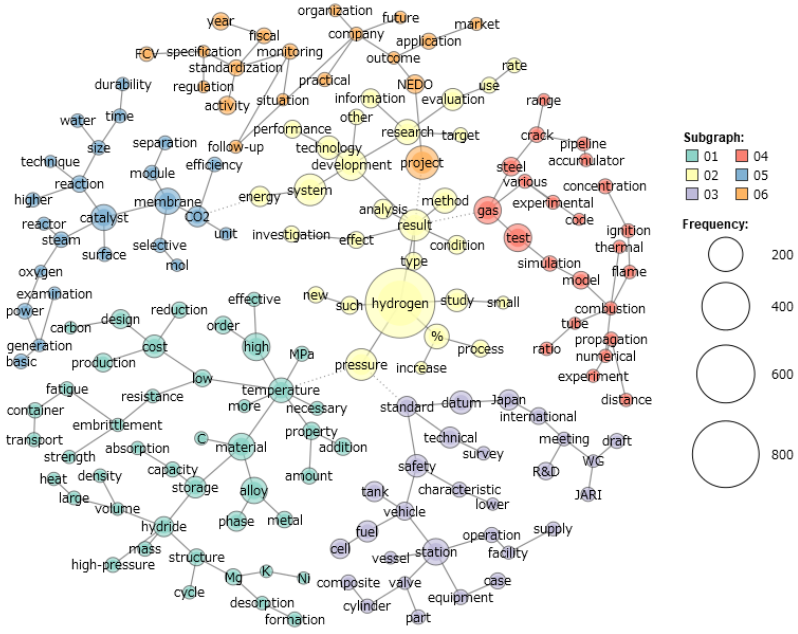

Figure 2 Network visualization of keywords observed in the abstract of research published from NEDO on the safety studies of hydrogen refuelling station using KH-Coder

Although the term ‘RA’ was not used in the project, it has emerged as a keyword in safety studies in recent years. In the rest of this paper, an overview of the safety studies on HRSs that have been conducted in Japan was presented based on the type of HRSs.

3.1 Off-site HRSs

There are two types of off-site HRSs: compressed and liquefied HRSs. Kikukawa et al. (2009) identified the hazards or accidental scenarios of liquefied HRSs using Hazard and Operability study (HAZOP) and Failure Mode and Effects Analysis (FMEA), and qualitatively evaluated the risks of the scenarios using risk matrices. However, no other RA studies for liquefied HRS have been reported.

Kikukawa et al. (2008) identified the accidental scenarios of compressed HRSs using HAZOP and FMEA and qualitatively evaluated the risks of the scenarios using risk matrices. In addition, Kikukawa (2008) conducted quantitative consequence analysis and safety verification for minor hydrogen leakage. The results were utilised to establish current safety codes and technical standards related to Japanese HRSs. However, although the consequences of a part of the scenarios were quantitatively estimated and evaluated, the qualitative evaluation of the risks were performed using simple process configurations. To address this, after approximately 10 years, Suzuki et al. (2021a) conducted a quantitative risk assessment (QRA) using the most current information on HRS technology and updated the RA results prior to the widespread increase in the number of stations.

Other studies related to the RA of compressed HRSs were conducted during the 10 years. For example, some studies attempted to improve the methodology related to the frequency analysis of hydrogen-based technology, such as HRSs. Kodoth et al. (2018) estimated the uncertainty and accident rate in HRSs, which is fundamental to the challenge of the lack of hydrogen failure data in HRSs, using a time correlation model. In addition, Kodoth et al. (2019) identified some appropriate failure estimators and life parameters for HRS, which are crucial for reducing uncertainties associated with risk and reliability quantification. Additionally, Kodoth et al. (2020) proposed a leak rate estimation using three approaches (non-parametric, leak-hole-size, and time-based evaluation methods). Further, some studies on RA and safety distance estimation have focused on hydrogen dispensers. For example, Hirayama et al. (2018) qualitatively evaluated the risks involved in the installation of hydrogen dispensers in public areas using risk matrices and concluded that the risks can be considered acceptable. In addition, Hirayama et al. (2019) proposed a specialized scheme that can be used to evaluate safety distances for hydrogen dispensers using an open access software and a widely-used calculation application. Suzuki et al. (2021b) estimated the quantitative risk derived from a hydrogen dispenser unit using multi-physics system-level modelling and in-depth simulation. Moreover, as an example of studies on safety measures, Sakamoto et al. (2018) evaluated the significance of safety measures in the event of simultaneous multiple safety measures failures, determined the combinations of safety measures failures that could lead to accidents, and suggested a measure for preventing and mitigating the accidental scenario by combining the physical model with a statistical method.

In addition to studies on the explosion or fire risk of HRSs, there are studies related to the public acceptance of HRSs and comprehensive RA. For example, Ono et al. (2017) characterized the risk perception of HRSs and analysed the acceptance of HRS by classifying people according to attributes, such as knowledge of hydrogen and risk perception characteristics. In addition, Ono et al. (2017) analysed changes in the perceived acceptability of HRSs in response to the provision of relevant risk and safety information, and the effects of these changes on the general risk perception of HRSs. Hienuki et al. (2021) conducted a questionnaire survey to analyse the public acceptance for the implementation of hydrogen self-refuelling stations. In addition, Hienuki et al. (2020) established a method to identify the comprehensive risks of hydrogen energy systems, such as the social (economic and policy) impact of hydrogen production, individual quality of life, and the well-being of the society.

3.2 On-site HRSs

Organic hydride HRSs, which utilise methylcyclohexane, have attracted attention owing to their advantages, such as maintaining a liquid phase at ordinary temperature and pressure. Accordingly, some studies have attempted to identify accidental scenarios and qualitatively analyse the risks of these HRSs. For example, Nakayama et al. (2016) identified a large number of accidental scenarios triggered by various external factors using a Hazard Identification study and conducted qualitative RAs using risk matrices. Further, Suzuki et al. (2021c) identified accident scenarios caused by internal factors, such as deviations of the processing parameters from normal operation and human factors during start-up and shutdown operation procedures. In addition, Nakayama et al. (2019) qualitatively analysed security risks, such as terrorist attacks or managing disgruntled employees using the American Petroleum Institute Standard 780. Other studies have conducted quantitative consequence analysis and RA. For example, Tsunemi et al. (2018) conducted a quantitative screening-level RA. Furthermore, Tsunemi et al. (2019) identified the accidental scenarios that are required to conduct a detailed RA, and estimated the risk for certain scenarios, such as hydrogen leak from some components of the accumulator and dispenser units in an HRS. In addition, Tsunemi et al. (2017) estimated the

consequences and damage that could result from the explosion and heat caused by the release of methylcyclohexane or toluene. Further, Nakayama et al. (2017) observed a domino effect scenario caused by the rupturing of hydrogen cylinders heated by the radiation heat flux from a methylcyclohexane pool fire, and quantitatively analysed the consequences of the scenario using simulations, after which they proposed safety measures for the prevention and mitigation of this scenario.
For HRSs that utilise electrolytic hydrogen generation system, there are no studies on the direct assessment of the risk of the HRSs; however, Kasai et al. (2016) conducted a qualitative RA for an electrolytic hydrogen generation system. For other type of HRSs, such as steam reforming or ammonia HRSs, there are no published studies on their RAs.

3.3 Other types of HRSs

As Japan has limited space, multiple-energy refuelling stations, which can supply a few types of energy, such as gasoline, CNG, and hydrogen, can ensure the efficient utilization of space. These stations may exhibit some kind of scenarios that are not present in off-site and on-site stations. For example, Sakamoto et al. (2016) and Kuroki et al. (2018) focused on a domino effect scenario that a massive gasoline pool fire forms at a gasoline dispenser, and the damage of a cold evaporator by thermal radiation. Although there may be similar scenarios to the domino effect scenarios, they are yet to be assessed.

4. Conclusions

This study aimed to comprehensively review the safety studies conducted in Japan, particularly, the RAs, and to provide useful insights on the direction of future studies on the safety of HRSs. As indicated in Sections 2 and 3, the results of the comprehensive review revealed that Japan has actively participated in the safety studies for HRSs and has achieved results. For example, for compressed HRSs, not only qualitative and quantitative RAs but also other studies related to public acceptance have been conducted, indicating that the safety studies for compressed HRSs are adequate for the social implementation of the widespread use of compressed HRSs. Additionally, RAs of organic hydride HRSs have been extensively conducted, and the accumulation of the knowledge is one of the strengths of Japan. In contrast, there are few studies on the RAs of liquefied HRSs and on-site HRSs except the organic hydride HRSs. Therefore, it is essential to conduct the RA for these HRSs and to mutually evaluate the results, including those of compressed and organic hydride HRSs, to contribute to the decision-making of the social implementation of HRSs in the future.

Acknowledgments

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