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A Systematic Literature Review on Safety of Hydrogen as a Marine Fuel

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In this paper a systematic literature review on safety and risk assessment at ports storing and transferring liquid or gaseous hydrogen is performed. Regulations and standards for hydrogen safety such as the IGF code and various ISO standards have been considered. In addition, various classification societies have issued guidelines for assessing hazards and risks of hydrogen storage at ports and during bunkering, such as DNV, Lloyds, Bureau Veritas and ABS. International and regional maritime organizations have also contributed to the systematic understanding and enforcement of risk assessment methodologies. The European Maritime Safety Agency (EMSA) has published a comprehensive report on the use of hydrogen as a marine fuel and the Society for Gas as a Marine Fuel (SGMF) has issued a guide on the use of hydrogen as marine fuel. The International Association of Ports and Harbors (IAPH) has issued checklists related to truck-to-ship and ship-to-ship bunkering. In addition, a literature review is conducted for the safe use of hydrogen as an alternative marine fuel together with risk assessment studies performed in the last 10 years. The aim of this review is to investigate scientific and harmonization gaps of hydrogen safety of the marine sector within the EU.

* 1. Introduction

The use of alternative marine fuels has been increasingly considered in recent years as a viable option for the shipping industry to achieve near-zero emissions, in line with the IMO's strategy for the reduction of ship emissions (IMO, 2023). Hydrogen, ammonia, biofuels, and methanol, are considered key solutions for accomplishing this goal (Jayabal, 2024). However, each of these fuels presents significant safety challenges that must be addressed. This paper focuses on the safety concerns associated with hydrogen use.

Ustolin et al. (2022) conducted a comprehensive review on the use of liquid hydrogen in the shipping sector, as an environmentally friendly alternative fuel. They analyzed liquid hydrogen safety aspects associated with the storage and handling on ships and during bunkering processes. The wide flammability range of hydrogen and the low minimum ignition energy pose significant safety issues. Hydrogen is explosive, easy to leak and capable of penetrating in pipes and tanks and may cause embrittlement which affects the integrity of the hydrogen storage equipment. Another safety concern involves the condensation of nitrogen and oxygen of air, due to the extremely low temperatures, in case of liquid hydrogen. This condensation can lead to the solidification of these gases, posing additional hazards. Moreover, the risk of low-temperature embrittlement of materials used in hydrogen storage and handling systems must be considered (Kim and Chun, 2023).

It is essential to consider safety aspects of hydrogen and perform risk assessment for storage and handling of hydrogen onboard, as well as for onshore storage and bunkering operations.

* 1. Regulatory framework
     1. International legislative bodies

Hydrogen has a low-flashpoint and therefore hydrogen-fueled ships are subject to the provisions of the IGF Code, which provides a regulatory framework to ensure ship safety, when gases or other low-flashpoint fuels are used (IMO, 2015). The IGF code incorporates specific requirements for the arrangement, installation, control and monitoring of machinery, equipment and systems, fire safety practices, fire-extinguishing systems, materials used and seafarers’ training.

The IGF Code focuses mainly on liquefied natural gas (LNG) and does not address specific safety issues of hydrogen. Therefore, hydrogen-fueled ships should be designed in accordance with the alternative design regulation which requires a comprehensive quantitative risk assessment (QRA) to be carried out demonstrating that the level of safety is equivalent to that achieved with conventional fuel designs (IMO, 2013). To support this process, the International Association of Classification Societies (IACS) issued guidance on risk assessment, as required by the IGF Code, without however including specific details dedicated to hydrogen (IACS, 2016). It introduces requirements for qualitative risk assessment whereby hazards, associated with the storage and handling of hydrogen onboard a ship, are identified, their consequences and likelihood are analyzed, risk is assessed, and risk mitigation measures are evaluated. These requirements do not cover risk assessment during the bunkering operations, namely ship arrival, approach and mooring, preparation, testing and connection, fuel transfer, and completion and disconnection, nor risk assessment of onshore port facilities and equipment. As there is no framework dedicated to bunkering activities, it is anticipated to adopt the relevant guidance provided for safety and risk assessment during LNG bunkering operations in accordance with ISO/TC18683 (ISO, 2021).

Moreover, there are various ISO standards that apply to onshore hydrogen systems, which can also be considered in the maritime sector. ISO/TR 15916 (ISO, 2015) has been established to provide guidance on the safe use of hydrogen in both gaseous and liquid form. It includes requirements for hydrogen storage systems, risks, hazards and safety properties, but does not cover safety requirements for hydrogen handling operations. Specific safety requirements are also defined for liquid (ISO, 2006) and gaseous hydrogen vehicles (ISO,2018), which could serve as advisory tools for maritime use

Port facilities capable of handling hydrogen to bunker ships, shall conform with the Seveso III Directive of the European Parliament (European Commission, 2012) which includes requirements for the prevention of major accidents from dangerous substances, such as hydrogen, and the limitation of their consequences for human health and the environment. This Directive is applicable to all installations storing more than 5 tonnes hydrogen (for lower tier requirements) or 50 tonnes (upper tier requirements).

* + 1. Classification societies

Several classification societies have issued guidelines for the safety of hydrogen-fueled ships. First, the Norwegian class, DNV, published a handbook on the use of hydrogen as a marine fuel (DNV, 2021). This handbook offers a brief overview of the use of hydrogen as a marine fuel, of the various hydrogen systems that may be applied onboard, and on safety issues that may arise. Insights on the relevant regulatory framework are also incorporated for the on-board safety consideration. Details on quantitative risk assessment are presented and risk-mitigation and risk-control measures are discussed, which contribute to safe design and operation.

Nevertheless, the first classification society that established guidance regarding the construction and operation of hydrogen-fueled ships was Lloyds. Lloyds (2022) incorporated specific consistent requirements for ships using hydrogen as fuel into the regulations for the classification of ships that are subject to the IGF code. The American Bureau of Shipping (ABS) proposed interim guidance for the design, construction of hydrogen fueled ships, focusing on safety aspects (ABS, 2023a). This guidance includes information associated with the ship design and layout, material and general pipe design, bunkering operations, fire safety and safety systems, and training. It further addresses the challenges posed by liquid or gaseous hydrogen fuel systems and mandates a risk assessment to consider human loss, damage to the environment or damage to the ship structure. To enhance such a risk assessment process, ABS has further adopted specific guidance notes for marine and offshore industries (ABS, 2020). In addition, Bureau Veritas (BV) issued rules for the arrangement, installation, control and monitoring of machinery, equipment and systems using hydrogen as fuel, with particular attention to safety assessment (BV, 2023). Specifically, it encompasses certain minimum requirements to be considered in a risk assessment required when hydrogen systems are implemented onboard a ship, including specific hazards and effects, as well as certain characteristics of events and failures. Further installation and operating requirements are determined by considering appropriate types of storage tanks, compatible materials for tanks and pipes, specific bunkering equipment, ventilation, fire safety and protection, safety systems for monitoring and controlling risk.

At the same time, the use of hydrogen through the application of the fuel cell technology is being studied and applied more systematically, resulting in the regulatory community working in this direction by issuing relevant rules and guidelines (IMO, 2022). Classification societies such as BV (2022), Lloyds (2023) and ABS, (2023b) have published relevant guidelines.

* + 1. International and European associations

International and regional maritime organizations have sought not only to enhance knowledge on the application of hydrogen in the shipping industry but also to contribute to the systematic understanding and enforcement of risk assessment methodologies.

European Maritime Safety Agency (EMSA) published a comprehensive report on the use of hydrogen as a marine fuel. It provides information on the properties of hydrogen, which contribute to various risks associated with its handling onboard, and the production of hydrogen (EMSA, 2023). This report considers “green hydrogen” produced mainly from renewable energy sources and examines its sustainability, availability and suitability. Greenhouse gases emissions and air pollution from NOx, SOx or PM are assessed for green hydrogen in combustion engines and fuel cells and compared to heavy fuel oil and LNG. Green hydrogen contributes to decarbonisation in maritime transport, because it generates relatively zero GHG emissions and significantly eliminates combustion products. Albeit, it is possible to contribute to indirect GHG release due to hydrogen slip effect where hydrogen leaks through pipes or storage tanks. Another challenging aspect of using hydrogen is its suitability due to storage and distribution issues. Important peculiarities exist in the construction of the storage tanks and the pipeline network due to high pressure or temperature, the material composition which is prone to embrittlement and the distribution cost of this fuel. This report also includes a techno-economic assessment that evaluates hydrogen application against conventional and other alternative fuels.

In addition, EMSA offers an extensive analysis to identify gaps related to the current safety and environmental regulatory framework that should be applied during bunkering operations, storage and handling of hydrogen onboard the ship. Several ISO standards, IMO regulations and requirements, guidelines published by various associations, including IBIA (International Bunker Industry Association), SGMF (Society for Gas as a Marine Fuel), SIGTTO (Society of International Tanker and Terminal Owners), classification societies, and European and National regulations are discussed. As safety regulations are practically in the development phase, EMSA proceeded to assess a series of risk-based case studies which highlight the commercial and safety implications of using hydrogen as a marine fuel. HAZID assessment is conducted in three types of fuel system configurations: a) H2-Fuelled Ro-Pax Vessel (with a compressed H2 tank and fuel supply system), b) H2-Fuelled Product Carrier (with a compressed H2 system), and c) CH4-to-H2 conversion and H2 use onboard Product Carrier, Ferry and Very Large Crude Carrier.

At the same time, similar, yet reduced, information has been published by the Society for Gas as a Marine Fuel (SGMF) through a guide dedicated to improving knowledge on the use of hydrogen as marine fuel (SGMF, 2023). It briefly describes its physical properties, its various production methods, the mandatory maritime regulatory framework, as well as special safety, technical and training issues. It emphasizes that, given the lack of data on hydrogen use in the shipping industry, only qualitative risk assessment is currently feasible and reliable.

Of considerable interest and assistance are the checklists published by the International Association of Ports and Harbors (IAPH) aiming at enhancing safety during hydrogen bunkering operations (IAPH, 2022). These checklists are related to truck-to-ship and ship-to-ship bunkering, providing specific instructions for completing relevant specialized checklists related to the various phases of the bunkering process. In particular, they include information on the preparation phase, the pre-operation phase, the alignment and agreement phase, the connection testing phase, the transfer phase and the post-operation phase. Some checklists correspond to the bunker operations supervised by a Bunker Facility Operator, some to the bunker terminal, and others to the receiving ship at a site outside a terminal.

* 1. Literature review

The scientific community has lately contributed to systematic research into the safe use of hydrogen as marine fuel, with the first risk assessment studies on the application of hydrogen as a marine fuel appeared in 2020. Aarskog et al. (2020) carried out a quantitative risk assessment (QRA) to investigate the compliance of a high-speed passenger ferry design powered by hydrogen fuel cells with the requirements of the IGF code. Fatality risk was calculated for the phases of operation and mooring, but not for the phase of bunkering. First, the preliminary hazard identification for the installed hydrogen systems was conducted, leak frequencies were calculated, catastrophic rupture of hydrogen storage system was predicted and the consequences, in terms of human loss, were assessed by implementing CFD calculations. Tofalos et al. (2020) applied a QRA methodology to examine the safe use of hydrogen compared to LNG as a fuel for a bulk carrier. Fuel leak accidents occurring during the bunkering operations were considered and pool and flash fire, and explosion scenarios were developed. Safety zones were further determined on the basis of the overpressure, pressure and radiation limits, where LH2 leaks were revealed to be smaller and have shorter lifespan than those of LNG.

Feng et al. (2021) identified the most critical hazards encountered during a shore-based bunkering operation of a hydrogen-fueled bulk carrier and proceeded to risk assessment assuming the hose rupture hazard. FLACS software was utilized to simulate the dispersion of hydrogen contributing to the calculation of the individual risk that demonstrated the need to implement suitable measures to control and mitigate the risk. Such measures were discussed and bunkering restriction areas were defined. Vairo et al. (2023) developed a combined methodology that utilizes decision trees, CFD and a data-driven approach to predict conditions that could lead to accidents, with a focus on the application of fuel cells in ships. Ryu et al. (2023) performed a QRA to assess the risk of hydrogen release in a fuel preparation room on a ship. First, an event tree was developed to identify typical accidental scenarios taking into account the installed safety systems. Hydrogen release and dispersion were then analyzed through a mathematical model for numerical CFD calculations, where it was revealed, through simulation, that dispersion is affected by various factors, including the layout and size of the equipment and the location of the venting system.

Other research focuses exclusively either to the probability of hydrogen release or to the consequences that are parts of a risk assessment. Aneziris et al. (2023) conducted a risk assessment that included, among others, hydrogen bunkering from a tank at a port to a fueled ship. The assessment focused on two key critical areas, that is the tank area at the port and the area around the fueled ship. For each of these areas, one operational phase was analyzed, namely the storage of the hydrogen in the tank at the port, and the transfer of the hydrogen from the tank to the fueled ship, by implementing the master logic diagram (MLD), fault tree and event tree techniques. Zhang and Jiang (2023) assessed the fire risk (in terms of probability) of hydrogen storage of ship hydrogen-fueled ship by developing three fault trees associated with hydrogen leakage, ignition source, and failure of remedial measures. Choi and Jeong (2023) applied CFD calculations to examine the dispersion of hydrogen under various wind conditions with the aim of aiding risk assessment and establishing safety criteria for hydrogen leakages occurring during bunkering of hydrogen-fueled ships. Soto et al. (2024) leveraged the Fluent code to develop a CFD procedure to investigate the consequences, in terms of explosion, resulting from the release of gaseous hydrogen due to blow-out gasket failure and dispersion for fuel storage below the ship's deck. This research contributes to strengthening explosion risk assessments, which constitute part of a QRA.

* 1. Conclusions

This paper provides a literature review on the safety of using hydrogen as a marine fuel. It discusses the key regulations, standards, and classification society guidelines relevant to the handling of hydrogen in ports and onboard ships. Additionally, studies involving QRAs to assess hydrogen safety in shipping were collected and reviewed. While the literature on hydrogen use on land is extensive, research focused on port facilities and marine activities involving hydrogen remains limited. Most QRAs currently conducted primarily address the design of hydrogen-fueled ships based on alternative design requirements. There is no QRA for storage and handling in port areas, and few studies have conducted risk assessments during bunkering operations, particularly for each of the available bunkering methods (ship-to-ship, tank-to-ship, truck-to-ship).

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