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HAZID-BASED RISK ASSESSMENT OF HYDROGEN-DIESEL DUAL-FUEL MARINE ENGINE SYSTEMS

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ABSTRACT

The maritime sector is undergoing a significant transformation to meet global emission targets. Hydrogen-diesel dual-fuel (HDDF) engines are considered a promising solution for the transition to low-carbon shipping. This study examines HDDF marine engine systems from a risk and safety perspective. The Hazard Identification (HAZID) methodology was used to identify potential hazards during the design phase. The system was analysed by an expert panel. The findings revealed risks in critical components such as storage, boil-off gas (BOG) management, and hydrogen injectors. Existing safety measures are evaluated, and further improvements are recommended. This study provides a safety-oriented roadmap and a comprehensive database, useful for future risk analyses.

Keywords: Hydrogen-Diesel Dual Fuel, HAZID, Maritime Safety, Risk Assessment, Decarbonisation

INTRODUCTION

The maritime sector is evolving to meet environmental targets. The International Maritime Organization's (IMO) Fourth GHG Study (2020) states that maritime energy demand is primarily met by heavy fuel oil (HFO), followed by marine diesel oil (MDO) and marine gas oil (MGO). This heavy reliance on fossil fuels leads to significant air emissions that must be mitigated [1]. In response, international initiatives are promoting low-emission fuels and carbon-reduction technologies [2]. To support these goals and comply with IMO regulations, various methods have been adopted [3],[4]. In this context, alongside battery systems, the use of alternative marine fuels, such as liquefied natural gas, methanol, hydrogen, and ammonia is being encouraged to reduce emissions [3],[5].

While various alternative energy sources are being explored, hydrogen stands out as a particularly promising candidate due to its unique chemical properties and environmental advantages. Hydrogen is recognized as a zero-carbon fuel and is often referred to as the "ultimate fuel" [6],[7] as it possesses a high calorific value and emits only water upon combustion [6]. Diesel engines remain the most popular for marine propulsion due to their flexibility and efficiency.

Furthermore, the versatility of modern diesel engines facilitates a transition to cleaner energy, as they can be adapted to operate on alternative fuels or dual-fuel configurations with minimal structural modifications and downtime [8]-[10]. There is growing academic interest in hydrogen-enriched internal combustion engines, and hydrogen-diesel dual-fuel (HDDF) engines are increasingly regarded as a promising solution for low-carbon maritime transport [11]. In this study, HDDF marine engine systems are analysed in terms of operational risks and safety using Hazard Identification (HAZID) methodology.

METHOD AND MATERIAL

Hazard Identification (HAZID)

The HAZID technique is derived from HAZOP and used during the conceptual design phase to ensure risks are identified and eliminated prior to implementation [12]-[14]. HAZID is a structured brainstorming method involving interdisciplinary experts, in which each facility or operation is examined using guidewords [13]. The HAZID procedure involves breaking the system down into its key nodes, selecting appropriate keywords for each node, and analysing potential hazardous events [13]. Identified hazards are assessed in terms of existing protection layers, and additional safety measures are recommended to reduce risk [14]. This approach helps prevent costly design revisions and provides a foundation for a sustainable occupational health and safety management system (ISO 45001) [15]. The composition of the expert team involved in the application of the method is presented in Table 1.

Hydrogen-Diesel Dual-Fuel Marine Engine Systems

The proposed hydrogen–diesel dual-fuel internal combustion engine system integrates a liquid hydrogen (LH_2) fuel supply chain with a conventional diesel pilot injection system for stable, low-emission combustion. Hydrogen is stored in a cryogenic LH_2 tank with vent mast for safe discharge of boil-off gas (BOG). A cryogenic pump transfers the liquid hydrogen, which is vaporized via a vaporizer and seawater-based heat exchanger to obtain gaseous hydrogen (GH_2). The hydrogen stream is filtered, pressure-regulated, and controlled through a gas valve unit (GVU) before metering and delivery to the engine via hydrogen injectors. In parallel, diesel fuel is supplied from a service tank through transfer and high-pressure pumps for pilot injection. Multiple safety and control layers, including leak detectors, fire detection, pressure relief valves (PRVs),

emergency shutdown (ESD) signals, and purge systems, are integrated with a central control system and electronic control unit (ECU). These control interactions ensure safe operation by enabling rapid isolation, ventilation, and shutdown in case of abnormal conditions, while maintaining precise fuel ratio control during dual-fuel engine operation.

Table 1. Expert panel composition and qualifications.

Expert	Position / Experience / Education	Information
1	Oceangoing Chief Engineer / 14 years / Bsc.	Expert in Hydrogen-Diesel Dual-Fuel Marine Engine Systems and the maritime risk assessment process.
2	Oceangoing Chief Engineer / 8 years/ Msc.	Expert in Hydrogen-Diesel Dual-Fuel Marine Engine Systems and the maritime risk assessment process.
3	Oceangoing Chief Engineer – Academician / 10 years – 2 years / Msc.	Expert in Hydrogen-Diesel Dual-Fuel Marine Engine Systems and the maritime risk assessment process.
4	Oceangoing Chief Officer – Academician / 6 years – 4 years / PhD	Highly proficient in maritime safety and risk assessment, with specialized expertise in the HAZID methodology.
5	Academician / 5 years / PhD	Expert in Hydrogen-Diesel Dual-Fuel Marine Engine Systems and maritime risk assessment, specializing in HAZID methodology.

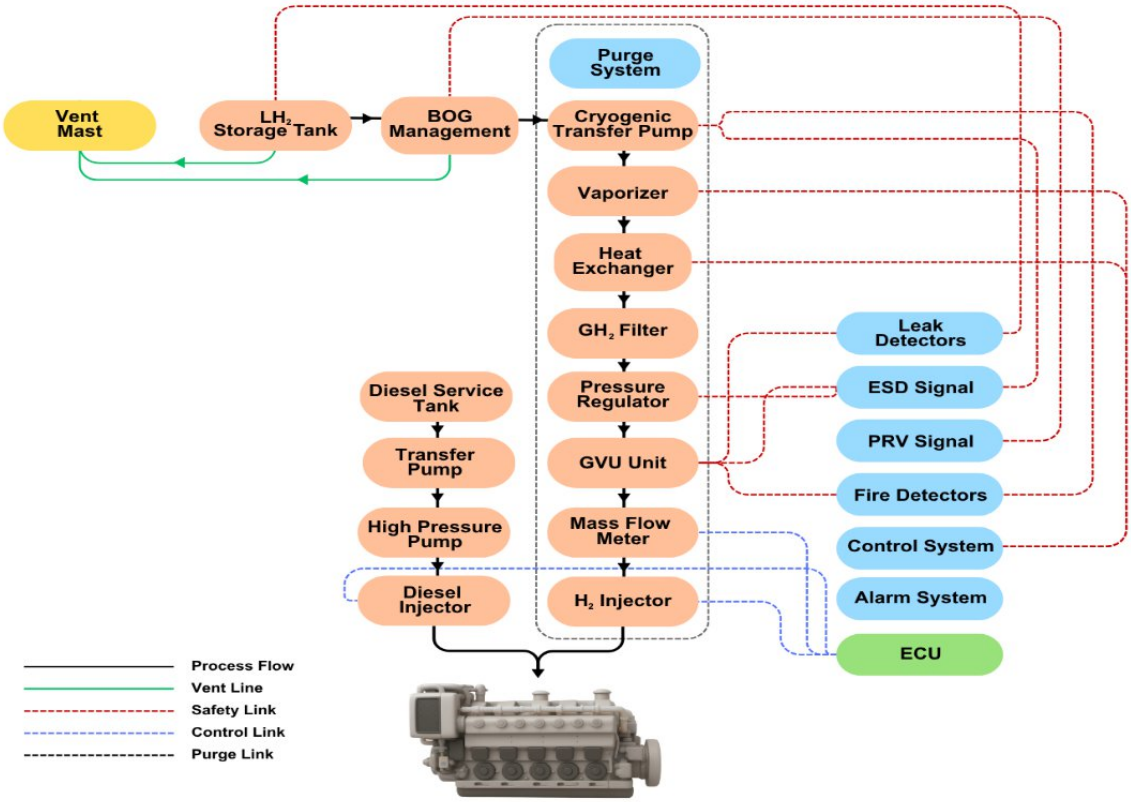


Fig. 1. Schematic diagram of the HDDF marine engine system.

RESULTS AND DISCUSSION

To ensure a comprehensive assessment, each component of the system was defined as a standalone node. These nodes are listed sequentially in Table 2. Also, a systematic HAZID study was conducted on the HDDF marine engine system, and the findings are presented in Table 3.

Table 2. System nodes defined for the HAZID analysis.

Node	Component of the System
1	LH_2 Storage Tank
2	BOG Management
3	Cryogenic Pump
4	Vaporizer / HX
5	GH2 Filter

6	Pressure Regulator
7	GVU
8	Flowmeter
9	Non-return Valve
10	Double Wall Pipe
11	H_2 Injector
12	Diesel Tank
13	Diesel Pump
14	HP Pump
15	Diesel Injector
16	Engine

Table 3. HAZID worksheet.

Node	Hazard	Possible Causes	Consequences	Existing Safeguards	Recommendations
N1	Overpressure	BOG accumulation, valve failure	Tank rupture, explosion	PRV, pressure sensors	Redundant PRV, continuous monitoring
N1	LH2 leakage	Tank insulation failure	Cryogenic burn, flammable cloud	Leak detection, insulation	Periodic inspection
N2	BOG system failure	Control malfunction	Pressure rise in tank	Vent mast	Backup control system
N3	Pump failure	Mechanical fault	Fuel supply interruption	Alarm system	Redundant pump
N3	Seal leakage	Seal degradation	Hydrogen release	Leak detection	Maintenance schedule
N4	Low temperature	Heat exchanger failure	Incomplete vaporization	Temperature control	Redundant heating
N4	Overheating	Control failure	Material damage	Sensors, alarms	Automatic shutdown
N5	Blockage	Particle accumulation	Reduced flow, pressure drop	Differential pressure monitoring	Filter replacement plan
N6	Overpressure downstream	Regulator failure	Pipeline rupture	Pressure relief, ESD	Dual regulator system
N6	Low pressure	Malfunction	Engine instability	Sensors	Backup control
N7	Valve failure (fail open)	Actuator fault	Uncontrolled hydrogen flow	ESD system	Redundant valves
N7	Failure to close	Control failure	Fire/explosion escalation	Leak detection, ESD	Periodic testing
N8	Incorrect reading	Sensor fault	Wrong fuel ratio	ECU control	Sensor redundancy
N9	Backflow	Valve failure	Combustion instability	Check valve	Redundant valve
N10	Inner pipe leak	Corrosion, fatigue	Hydrogen accumulation	Leak detection, ventilation	Integrity monitoring
N10	Outer pipe failure	Structural damage	Gas release to engine room	Ventilation	Structural inspection
N10	Ventilation failure	Fan failure	Gas accumulation	Gas detection	Backup ventilation
N11	Backfire	Improper mixing	Flashback, explosion	ECU control	Flame arrestor
N11	Injection failure	Blockage	Power loss	Monitoring	Maintenance
N12	Fuel leakage	Tank damage	Fire risk	Containment	Inspection
N13	Pump failure	Mechanical fault	Fuel supply loss	Alarm	Redundancy
N14	Overpressure	Control failure	Injector damage	Pressure control	Relief valve
N15	Malfunction	Wear	Poor ignition	ECU control	Maintenance
N16	Insufficient air	Turbo failure	Incomplete combustion	Sensors	Redundant air supply
N16	Abnormal combustion	Fuel imbalance	Knock, damage	ECU, alarms	Shutdown logic

N16	Hydrogen accumulation	Leakage	Explosion risk	Ventilation, detection	Improved airflow
N16	High temperature	Combustion issue	Fire hazard	Monitoring	Thermal protection

CONCLUSIONS

This study examined the safety and operational risks of a HDDF marine engine system. A hazard identification process was carried out on 16 critical components using the HAZID methodology. The analysis revealed that components pose risks such as overpressure, leakage and backfire. Strategic improvements are recommended to enhance system reliability.

The approach, applied during the design phase, helps prevent costly revisions and safety breaches in operations. The findings show complex interactions affecting both individual system components and other critical points and processes. This represents a key step toward establishing a sustainable occupational health and safety management system.

This qualitative study presents a safety-focused roadmap for integration of low-carbon maritime transport technologies. The identified hazard categories and recommended measures aim to ensure the system's technical and operational integrity. The study also forms a comprehensive database to support future risk assessment studies. Future work will extend this study through quantitative risk assessment and experimental validation to enhance the reliability and applicability of HDDF marine engine systems.

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