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Comparative safety analysis of engine room fires with different marine fuels of MGO, LPG and H2

Vadym Nechyporenko[a] and Byongug Jeong[a,b]

[a]Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK; [b]Europe-Korea Marine and Ocean Engineers Association (EKMOA), Southampton, Hants, UK

ABSTRACT
This research project is designed to investigate the behaviour of fires resulting from hydrogen leakage in engine rooms and evaluate the associated fire risks, aiming to compare these risks with those posed by traditional fuels which can be used in the shipping industry today. The study employs a model of the engine room constructed according to the original dimensions of the vessel under study. The primary objective of this research was to determine if the fire risk associated with hydrogen would be higher or lower than that of traditional fuels. To achieve this, a series of simulation scenarios were meticulously executed and subsequently analysed. The outcomes of the simulations indicate that hydrogen fires do not present a higher threat when compared to fires fuelled by marine gas oil or liquefied petroleum gas. Notably, hydrogen exhibits superior fire behaviour, characterized by the absence of smoke development and relatively less harm to machinery and crew, thus outperforming conventional fuel fires. This finding suggests that hydrogen-related fire risks can be brought under control and highlights its potential as a comparatively safe fuel choice in the maritime domain.

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Hydrogen; fire; dispersion; safety; simulation; safety assessment; emissions

Introduction

The greenhouse gases (such as methane (CH4), carbon dioxide (CO2) nitrogen oxides (NOx)) have been described as one of the key factors of climate change nowadays (Sonwani & Saxena, 2022). The transportation industry plays significant role in the boosting of this process which negatively affects the environment of our planet. Since more than 80% of worldwide traffic in goods is carried out by sea (UNCTAD, 2022), then it is crucial to mitigate greenhouse gases emissions from ships in maritime sector. According to the International Maritime Organisation (IMO) report, the greenhouse emissions caused by the shipping industry have grown by 9.6% from 2012 to 2018. According to these estimates, there will be a 90% increase in greenhouse gas emissions from 2008 to 2050 if no preventative measures are taken (International Maritime Organization IMO, 2020). Thus, International Maritime Organisation (IMO) has established a goal of decreasing shipping emissions at least by 50% by 2050 (Joung et al., 2020). However, there are some substantial changes have to be made in the maritime sector in order to achieve such significant percentage number.

In order to accomplish zero-emission target, hydrogen is currently being researched as an alternative fuel for shipping industry, alongside other alternatives such as ammonia, methanol, and electric-driven vessels, but hydrogen is the most promising alternative fuel in a long perspective. One of the biggest superiority of hydrogen as an alternative fuel does not contain carbon or sulphur atoms, which lead to simplicity of the combustion equation that includes only water vapour as a byproduct. Therefore, it makes hydrogen an excellent option for reducing emissions the maritime industry. Hydrogen storage requires a lot of volume in vapour form, that is why this substance should be compressed or cooled down for convenient transport process. Also, H_2 does not pose the threat to the marine environment in case of spillage, since the hydrogen is highly buoyance and volatile.

However, there are several potential issues with this endeavor. Firstly, handling liquid hydrogen is dangerous because of its cryogenic temperature (−253 °C), which can result in cold burns (Osman et al., 2021). Secondly, when enough hydrogen is mixed with oxygen, it produces a tremendous amount of energy, resulting in explosions. Furthermore, because hydrogen is colorless and odorless, identifying leaks in a hydrogen system is becoming to be a challenge. Because hydrogen flame is invisible, it might be difficult to extinguish as well. The risk of a fire can be increased if hydrogen is not properly isolated, since oxygen in a vicinity of the storage compartment can condense (Crowl & Jo, 2007). Finally, hydrogen production has certain limitations in meeting all the potential demand in the marine sector.

CONTACT Byongug Jeong byongug.jeong@strath.ac.uk Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK

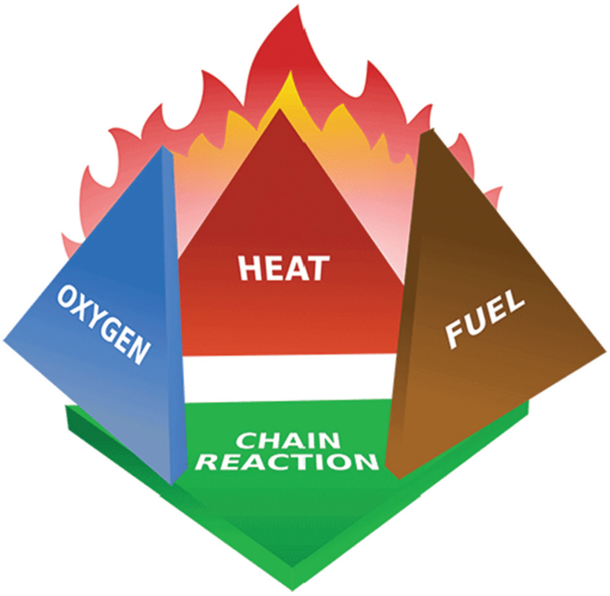

Figure 1. Fire tetrahedron (FRA Network, 2018).

A lot of safety precautions have to be taken to ensure hydrogen safe storage and operation in the engine room, because this part of vessel has the most favourable condition for Fire Tetrahedron occurring (see Figure 1). The Fire Tetrahedron involves heat, oxygen, fuel and chain reaction (FRA Network, 2018). The engine room itself includes these components: a massive amount of oxygen via the ventilation system in order to maintain excessive atmospheric pressure for the machinery; a significant amount of heat from the machinery equipment surfaces; a huge amount of fuel in the form of any combustible material such as fuel for the propulsion plant (marine diesel oil, hydrogen, etc.), lube oil, oil rags, etc.; and a chain reaction in case fire occurs.

As a result, it is crucial to analyse fire safety limits and potential of the engine room in compared to traditional fuel types. Based on the results of the analysis, it will be necessary to develop a method for hazards control for maintaining a high safety standard. Thus, a focus of this research project will be on improving and assessing the fire safety of hydrogen where it is used as a marine fuel by analysing engine room fire simulations risks and determining the severity of those risks for a case ship.

Literature and critical review

Utilizing hydrogen as a fuel

Decarbonization of the shipping sector is unavoidable, so the necessity to implement zero-carbon marine fuels becomes a more and more urgent task for humankind. There are several options for minimising the carbon footprint effect of the ships, which are hydrogen, ammonia, liquefied natural gas (LNG), ethanol, methanol, or biofuels. Hydrogen has a few strengths over the other options, the most notable of which is the highest Low Heat Value (LHV) energy density of 120 MJ/kg for both compressed and liquid hydrogen (Cheliotis et al., 2021). The characteristics of some essential alternative fuels are depicted in Table 1. It is approximately three times higher than conventional fuels such as Marine diesel oil (MGO) or heavy fuel oil (HFO), with a heating value of around 40.9 MJ/kg (Huth & Heilos, 2013).

Hydrogen is widely regarded as the most environmentally friendly marine fuel for various reasons. Firstly, it superiors LNG and methanol in terms of environmental performance, with no waste gas emissions. Secondly, hydrogen can be produced by a variety of renewable resources, increasing its potential for renewal. Thirdly, it is consistent with government policies and meets IMO rules for emissions reduction. Also, hydrogen is more socially acceptable due to its good environmental impact (Ren & Liang, 2017). Additionally, hydrogen has the lowest volumetric energy density which can be considered as advantage in case of potential fire from a spillage.

From a practical perspective, based on this hydrogen energy density (low heating value) property, hydrogen can be described as an efficient replacement for conventional fuels. However, this hydrogen as a marine fuel has lots of disadvantages as well. The main challenge is maintaining storage conditions for the liquid stage of hydrogen. It will be stored either at extreme high pressure (up to 700 bars) or cryogenic temperatures (around −253 degrees Celsius). Both methods of hydrogen storage at liquid stage require additional energy utilisation, which means some quantity of this fuel can be wasted for this process. However, in studies at Istanbul Technical University,

Table 1. Properties of alternative and conventional marine fuels (Cheliotis et al., 2021).

Fuel	Liquefied Temperature (°C)	Storage Pressure (Bar)	Renewable Synthetic Production Cost (MJ/MJ)	Energy Density LHV (MJ/kg)	Volumetric Energy Density (GJ/m^3)
Compressed Hydrogen	20	700	1.7	120	4.7
Liquid Hydrogen	−253	1	1.8	120	8.5
Methanol	20	1	2.6	19.9	15.8
Liquid methane	−162	1	2.3	50	23.4
Ethanol	20	1	3.6	26.7	21.1
Liquid ammonia	−34 or 20	1 or 10	1.8	18.6	12.7
Marine Diesel Oil	20	1	-	44	36.6
LPG (propane)	−42	5–7	-	49.6	25.3

environmental and economic assessments of methanol, ethanol, LNG, and hydrogen are evaluated, and it is determined that LNG and hydrogen are two the most viable alternative marine fuel (Deniz & Zincir, 2016).

Since Hydrogen is the first element in the periodic table, it has the smallest molecules, that is why the safe storage of its gas is more difficult than that of other gases. Hydrogen has a broad flammability range, is easily ignited, and also can self-ignite. A combination of such properties may increase total risk unless appropriate hydrogen safety procedures and practices are applied. Because the similar safety practices will not mitigate additional hazards, other better designs and more safety measures are expected when compared to other fuel systems.

The main difficulty is to avoid the chain of events which could lead to an accident if appropriate safety measures are not implemented and efficient. To detect, control, and reduce possible dangers associated with hydrogen use as a fuel, a well-organized risk assessment approach involving people with the appropriate expertise is required. Leaks in the onboard fuel storage and supply systems have the capability to cause high-risk situations (DNV, 2021).

As a result, knowing hydrogen and its safety-related features in a marine setting will be critical for the safe and efficient implementation of hydrogen as a ship fuel. Many major risk-related issues include the use of materials that are not completely compliant with hydrogen operation; the marine environment; reliable identification of process and operational aberrations; ignition-source control; and mechanisms for ensuring safe operations.

International regulations and rules

For marine internal combustion engines, hydrogen offers a promising alternative for achieving decarbonization in the shipping sector. But it's important to be aware of dangers with security issues involved. Every aspect of handling hydrogen on ships, including production, transportation, bunkering, storage, and use, needs to be carefully analysed for risks. This assessment's main goal is to make sure that secure and dependable designs and systems are created. It is possible to create a safe, reliable, and effective hydrogen system by carrying out the risk assessment early in the design process, in cooperation with system designers and architects (DNV, 2021).

The safety regulations and rules suggested by the IMO and a variety of Classification societies requirements, the FSA as a regulatory tool of the IMO, recommendations for fire accident evaluations, and research materials can assist in finding and evaluating the reliability of safety precautions in the most vulnerable places of the vessel, such as the engine room, in particular (McNay et al., 2019). This study uses a bowtie approach with prevention and mitigation focuses on the fire onboard and employed particular criteria to determine the importance and following impact of the safety regulations. It is recommended to put more effort on the left side of the bowtie, as these improvements can decrease the probability of fires by identifying and eliminating hidden root cause elements before the fire may occur.

The IGF code offers specific guidelines for the utilization of gaseous and low flash point liquid fuels on ships. Moreover, the alternative design approach outlined in the IGF code is essential to follow, particularly for hydrogen fuel vessels, as dedicated classification society rules for such vessels are currently under development (Aarskog et al., 2020). Furthermore, the mentioned study carried out a risk assessment for a concept design of a hydrogen-driven high-speed passenger ferry, focusing on fatality risk related with the hydrogen systems during operation and mooring in harbour. The findings state that the estimated risk related to hydrogen systems is limited, well below the anticipated risk tolerance level, by considering today's regulations.

Liquefied gas storage on ships is subject to the guidelines provided in Chapter 6.1 of the IGC Code (IGC, 2014) and International Code of safety for ships which use Gases or any other low-flashpoint Fuels (IGF code). The C-tank regulations must be followed when storing liquefied hydrogen at cryogenic temperatures, but due to the special hydrogen characteristics, including its flammability and low storage temperatures (IGF, 2015).

In terms of these two Codes, IGC and IGF, there is a study that analyses the regulatory deficiencies of these two international codes. The study found that LNG-fuelled ships are subjected to higher safety requirements under the IGF Code compared to the regulations for LNG carriers in the IGC Code. This difference stems from the brevity of LNG-fuelled ships, despite LNG carriers having a strong safety record. The study suggests that while the two Codes may not be fully identical due to different risk natures, clear technical justifications could lead to acceptable differences in regulations. It proposes specific areas in both Codes, such as machinery space, stress analysis on piping systems, and safety requirements for ducts and ventilation, to be thoroughly revised to bridge the safety requirement gaps for engine room systems. The study recommends that the IMO consider these findings during periodic reviews and potential amendments to the Codes. Even though the paper considers LNG as a fuel, a similar approach can be applied to Hydrogen as a potential marine fuel in the future.

Therefore, there are two basic strategies for fire safety evaluation using international regulations and guidelines: the regulatory approach and the good practice approach.

The regulatory approach to fire safety assessment, as dictated by the SOLAS international convention, is a method used to ensure consistent safety standards for vessels. Regulations are based on past accident experiences and current technology, providing guidelines for fire protection, detection, and extinguishing (IMO, 2001). The approach is useful for evaluating fire safety engineering design practices and may be applied to any vessel by both experienced and inexperienced personnel. The main advantage is its emphasis on achieving acceptable safety standards, but it has drawbacks. The implementation process is lengthy, causing delays in updating regulations to keep up with new technological developments. Additionally, the regulatory approach may overlook important aspects such as human factors. While it sets consistent safety standards, it may not be suitable for evaluating new fuel types like hydrogen, where regulations are not yet developed due to limited past experience and technology advancements (IMO, 2015).

The good practice approach for fire safety involves the usage of informal guidelines developed by organizations and individuals to establish and maintain safety standards for various marine activities. Classification societies or even international shipping bodies can act as these organisations, which have maintained a competitive edge in paving the road for hydrogen-powered ships, such as DNV or BV. For hydrogen-powered ships, they have a procedure for granting AIPs (approval in principle) and creating safety requirements. A manual for hydrogen-powered vessels has been released by DNV (DNV, 2021). The guidelines often reference or are based on IMO-SOLAS regulations, making them understandable and applicable to different systems. While user-friendly, the approach lacks consistency in evaluating complex safety aspects and its effectiveness depends on voluntary adoption by shipowners. It is a valuable initial step in evaluating the safety of new concepts, but it may not be effective for novel fuel types such as hydrogen due to a lack of conclusive evidence for its applicability (IACS, 2004).

Prior studies on the fire simulation

The fire risk assessment, as governed by rules and regulations, primarily adopts a qualitative approach. However, in this section, there will be a critical examination of scholarly papers that explore the practice of quantitative risk assessment in relation to fire safety.

The rapid burning of hydrogen gas in the presence of air or oxygen is referred to as hydrogen deflagration. When a deflagration occurs, the hydrogen burns subsonically, creating a flame front that spreads through the hydrogen and air mixture. Due to the rapid flame propagation, there is practically no chance to stop hydrogen combustion once it has begun. In enclosed spaces where hydrogen has accumulated, like hydrogen storage facilities or enclosed engine rooms on ships, deflagration can happen. When using or storing hydrogen, fire safety precautions are essential since the release of a significant amount of energy during a hydrogen deflagration can result in serious pressure increases and severe damage to structures and equipment. Thus, it is important to study hydrogen deflagration behaviour, and Tadej Holler does it in his work (Holler et al., 2022), where he describes the use of CFD (computational fluid dynamics) combustion modelling in managing hydrogen safety. The results of the modelling and its comparison with data from experiments therefore demonstrate the impact of the vessel's diameter and the hydrogen level at the start. The simulations were assessed by modelling flame propagation in different dimensional setups and flame regimes. It is worth mentioning that differences in results from various models are more significant in the wider vessel than in the narrower one. This paper emphasises that thorough theoretical simulations might offer more accurate forecasts than conservative predictions. The article provides insights into combustion behaviour and its key parameters, which could have practical applications in the maritime industry for steam boilers or hydrogen storage in vessels.

The (Alvarez and Giraldo, 2018) study compares different fire neutralization methods by utilizing the Fire Dynamics Simulator (FDS) as a supporting instrument. It focuses on the assessment of electrical fire hazards caused by electric cabinets, which contribute to over a tenth of all fire incidents. Three scenarios are considered: one without any protection applications, one with a pure agent extinguishing application and one with a already less hazardous design. The first scenario, without fire protection, exhibits high gas temperatures (up to 820°C) in the room, posing risks to the cubicle's mechanical integrity and personnel safety. The second scenario reduces the control room interior temperature by using an extinguishing medium, but may cause harm to adjacent structures due to heat spread. In contrast, the third scenario, implementing an inherently safer design, confines a fire to the original cubicle, safeguarding other cabinets in the room and protecting personnel.

The study underlines the importance of taking into consideration oxygen concentration and frontal ventilation in fire suppression strategies. The simulation results shows that a frontal ventilation might not be suitable for an inherently safer design application as it could lead to re-ignition of the flame. Net accident radiation is analysed to assess the consequences of the fire scenarios on human health. The first scenario poses a high incident heat flux that could cause burns in exposed personnel, while the protected scenarios do not pose such risks. The study concludes that an inherently safer design approach is recommended when the heat release ratio is exceptionally high, and an active system like a sprinkler system cannot guarantee the mechanical integrity of the facility. However, for lower heat release ratios, an extinguisher injection system linked to a smoke detection system is suggested for early detection and effective mitigation of the consequences.

Another study is focused on researching the natural gas leakage and diffusion in the engine room of LNG powered ships (Xie et al., 2023), which can indeed be adopted for hydrogen driven vessels. The study holds significant importance for the design of such ships, fire risk assessment, and explosion prevention. The research conducted a model experiment system with a scale ratio of 1:10 was set up, using helium gas as a substitute for natural gas. The experiment was aimed to understand the distribution of light gas concentration in the model engine room over time. In order to do that, it used CFD modelling to verify the experimental data and then simulated the behaviour of natural gas diffusion in a full-size ship's engine room. They analysed the impact of various factors, such as leakage amount, cabin temperature, ventilation conditions, and leakage location, on the concentration distribution of natural gas. The researchers found that the CFD model had good predictive power for the dispersion behaviour of light gas in the ship's engine room, and the simulation results aligned well with the experiment, with a maximum error of around 20%. The amount of leakage had a significant influence on the concentration near the leakage point, and higher initial volume flow and temperature of the leakage led to larger dangerous areas in the engine room. It was discovered that increasing ventilation flow was an efficient way to decrease the dispersion area and control the natural gas level in the engine room. Doubling the ventilation rate resulted in reducing the dangerous volume of gas diffusion to one-third of the original volume.

The paper provides insights into predicting the spatial and temporal distribution of gas diffusion concentration in the engine room environment accurately. Based on their findings, the researchers recommend installing gas early warning devices in natural gas pipelines and related equipment in the engine room to prevent and monitor gas leakage. Additionally, they propose setting the system to automatically increase the exhaust ventilation rate during normal operations to ensure safe gas discharge and diffusion in case of an unknown natural gas leak. Therefore, the research contributes valuable knowledge to improve safety measures in LNG-powered ships and prevent potential hazards associated with gas leakage and accumulation in the engine room. By understanding the behaviour of natural gas diffusion, the study aids in designing safer engine rooms and reducing the risks of fire and explosions on such types of vessels, including hydrogen-powered ships.

Another work discusses the use of computational fire simulations in the early stages of ship design to enhance fire safety management in the maritime industry (Kang et al., 2017). Despite ships being built in accordance with fire safety rules and regulations, ship fire accidents does not stop to occur due to the rapid spread and difficulty in controlling fires on ships. Computational simulation tools are employed during the ship design process to predict and mitigate fire propagation, allowing for better comprehension of heat and smoke tendencies based on various factors. The study proposes a framework that organizes computational fire simulations within the existing ship design process without requiring significant changes. This approach is particularly beneficial in the early design phase when detailed data is limited. The framework involves selecting target areas for fire simulations based on historical fire accident data and considering fire scenarios. It allows ship designers to assess the impact of heat and smoke dispersion and make informed decisions regarding the arrangement of spaces, corridors, doors, and openings. The simulations help in determining the most effective fire extinguisher specifications, nozzle arrangements, and fire safety plans for each design alternative. In this study, the application of the framework is demonstrated through a Ro-Pax ship design procedure, where simulations are used to assess fire safety in the machinery room. The integration of computational fire simulations with on-board incident management systems and training systems further enhances decision-making support for onboard crews during emergencies. Thus, the article highlights the value of computational fire simulations as a practical and cost-effective tool for improving fire safety in ship design. The proposed framework allows ship designers to make informed decisions about fire safety measures without drastically changing the existing design process. By utilizing computational fire simulations and continually updating fire safety plans, ships can be designed and operated with enhanced fire safety, potentially reducing the occurrence and impact of ship fire accidents.

The 3D modelling was used as a part of the methodology in the study about the prediction of heat and mass transfer via an intumescent paint applied to an on-board high-pressure GH2 storage tank to enhance its fire resistance (Kim et al., 2017). This 3D simulation is essential for understanding the initial thermal conditions and heat transfer characteristics of the tank without any thermal protection. The data obtained from the 3D simulation of the bare tank is then used as a boundary condition for the subsequent 1D numerical model of the intumescent paint behaviour. The 1D model is employed to predict the expansion process of the intumescent paint, considering local changes of heat and mass within the coating. This model aims to simulate the thermal protection provided by the intumescent paint during a fire event. Since validation and input data for this model come from the 3D simulation, it plays an important role in the overall methodology of the paper, even though the main analysis and conclusions are based on the 1D modelling of the intumescent paint.

Also, the FDS can be implemented to simulate the behaviour of fire for different types of fuel, as in the study on the assessment of ammonia as a marine fuel for engine room fire safety (Pomonis et al., 2022). The paper conducts several simulation scenarios with ammonia fire, dispersion of ammonia as a gas, and simulation of fir for such conventional fuel types as MGO and LNG. The research monitors essential parameters such as heat release rate and temperature distribution, visibility and toxicity levels, and oxygen concentration over time. The work finds that ammonia does not carrier a higher threat than natural gas or diesel fires. Ammonia's fire behaviour is found to be better than that of conventional fuels in terms of soot formation and potential machinery damage. The research concludes that ammonia's flammability limits and thermal properties result in slower dispersion, reducing the likelihood of an ammonia fire and making it manageable. The study uses PyroSim software as its core tool; therefore, a similar approach can be implemented to evaluate hydrogen fire behaviour.

Additionally, FDS can be used for modelling fire extinguishing systems in ship engine rooms, as in the Bellas et al. (2020). The paper compares the FDS simulations with full-scale test results conducted according IMO Circulars. The simulations include different fire scenarios, such as exposed and concealed diesel and heptane sprays, as well as thermal management experiments. Overall, the FDS simulations show good agreement with experimental results for most scenarios, but some complex phenomena like reignition are not accurately captured. The study concludes that FDS can be applied in a performance-based design approach for water mist fire extinguishing systems in ship machinery spaces, but improvements in modelling certain fire behaviours are needed.

In another study (Wu et al., 2018), FDS and CFD play crucial roles in modelling and simulating the fire development process, providing important information on critical temperature and smoke levels, which are essential for estimating the available safe egress time (ASET). Overall, the paper proposes a probabilistic method for estimating the fatality rate of fire accidents on ships, specifically focusing on critical temperature and critical smoke as the causative factors. It compares the *available* safe egress time (ASET) with the *required* safe egress time (RSET), in order to estimate the fatality rate. As already mentioned, the FDS software is used to model the fire development and derive the ASET, taking into account critical temperature and smoke. The RSET is determined based on guidelines from the IMO. Thus, in the paper, FDS reconstructs the ship cabin, defines the fuels, sets the configurations of the fire accident, and derives the relationship between time and critical temperature. This method is applied to a real fire accident scenario, and the fatality rate estimated using this approach closely approximates real scenarios. Thus, the study underscores the importance of taking into account critical temperature and smoke in fire safety engineering, as the majority of fire fatalities are caused by smoke.

The research on the analysis of natural gas dispersion in the engine room space of LNG gas-fuelled ships, with an emphasis on potential fire and explosion threats caused by gas leakage (Xiao Jian Li et al., 2016), can also be applied to hydrogen dispersion. Similarly, this study also utilises CFD modelling to simulate gas dispersion under various conditions, including leakage rate, position and direction of release, temperature gradient, ventilation, and the presence of machinery equipment in the engine room. The CFD simulations demonstrate that gas dispersion is influenced by factors such as air flow, temperature gradient, and gas buoyancy. The presence of vortex flows in certain areas leads to gas concentration, which affects the effective arrangement and location of gas detectors. The study proves that CFD is an effective tool for simulating accidental releases of natural gas in the engine room space of LNG gas-fuelled ships. The results of the simulations provide insights into gas dispersion patterns under various conditions, which can help in designing effective safety measures and locating gas detectors to mitigate the consequences of accidental gas releases in confined spaces.

Lastly, CFD software, specifically FLACS, was used to analyse the behaviour of hydrogen dispersion and concentration distributions in the hydrogen fuel cell room (FCR) based on China's first new-built hydrogen-powered ship's parameters in the study on the safe design principles and leakage risks associated with the hydrogen gas supply system (Guan et al., 2023). The CFD performs a detailed simulation of various hydrogen leakage scenarios with different diameters and directions. By analysing the hydrogen concentration and dispersion in the FCR, the study suggests the optimal locations for hydrogen detectors and pipeline diameters for hydrogen gas supply systems, which ultimately facilitate the safe design of hydrogen-powered ships. The quantitative data obtained from the CFD simulations is valuable for optimising hydrogen safety in hydrogen-fuel-cell-powered ships and provides essential references for the safety design of such ships, especially in the early stages of their demonstrations.

As a result, the research papers discussed above share a common focus on enhancing fire safety engineering practices. This involves a design and structures assessment to reduce the fires impact and protect lives. The use of computer simulations is essential in this endeavour, as it enables the examination of different fire stages and their effects on materials. These simulations offer flexibility in modelling various fire scenarios, leading to comprehensive evaluations. However, it is important to mention that conducting such simulations needs a qualified team and considerable computational resources. Nevertheless, this approach is valuable in understanding the fire behaviour of novel concepts like hydrogen and other gas fuels used on ships, contributing to a more environmentally friendly future in the maritime industry.

Research methodology

Methodology flow diagram

To achieve a favourable result for the paper, it was essential to adhere to a well-defined methodology. Figure 2 depicts the step-by-step process through which the paper was meticulously designed and carried out. The following elaboration outlines the first, second, and third steps in this chapter. The fourth and fifth steps will be discussed in Chapter 4 and Chapter 5 of this research, respectively.

Identifying a pertinent case vessel

The optimal approach for simulating a hydrogen leak in an engine room involves utilizing an operational ship that operates on hydrogen fuel. However, currently, there are limited vessels of this nature in service, primarily consisting of prototypes powered by hydrogen fuel cells. Over the past few decades, the marine industry has witnessed an increasing trend in using gas, particularly LNG, as a viable marine fuel. This adoption has provided valuable experience and confidence in gas propulsion technologies. Furthermore, shipbuilders have progressively introduced dual-fuel engines for non-liquefied gas carriers, such as bulk carriers, which means that using the vessel's own cargo as a fuel is not a prerequisite. As a result, an LPG carrier Trammo Marycam was selected as the case vessel for study, as its cargo space could potentially be retrofitted for hydrogen transportation or adapted for use as a dry cargo carrier. The vessel is a 16,772-ton deadweight LPG tanker (Table 2), and it is assumed that vessels with a comparable design will be able to operate on hydrogen.

Selection of CFD software

Given the impracticality of assessing fire safety through real fire scenarios, the utilization of Computational Fluid Dynamics (CFD) platforms becomes imperative. These platforms, specifically those integrating fire-driven fluid flow simulations, such as the Fire Dynamics Simulator (FDS), serve as invaluable tools for discerning distinct fire attributes. For this reason, the PyroSim graphical interface for the FDS was chosen as the primary tool within this study, facilitating the simulation of different fire types and their behaviours (Thunderhead Engineering, 2023).

Originally, Fire Dynamics Simulator was created by National Institute of Standards and Technology (NIST). The software calculates the Navier-Stokes equation for a slow speed thermally powered flow, which has an impact on the distribution of smoke and heat produced by simulated fires (Floyd et al., 2012). The configuration of simulations with initial variables requires the use of the NIST Coding language. The simulation results are elucidated and visualized using the Smokeview interface.

PyroSim, a graphical interface designed to accommodate advanced FDS models, was employed in this project to execute fire simulations and define simulation parameters, circumventing the complexities of coding directly within FDS. This approach streamlined the process. Notably, FDS emerges as an important tool within the marine sector for simulating hazards and accident assessments.

Table 2. The key characteristics of the vessel.

Name of the vessel	*Trammo Marycam*
Type of the vessel	*LPG tanker*
Total length	*154,17 m*
Length between perpendiculars	*147 m*
Breadth	*26 m*
Depth	*16 m*
Draught	*8,8 m*
Total designed volume for fuel tanks	*1425 m3*

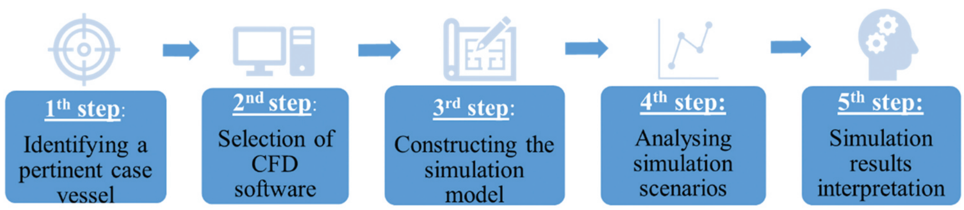

Figure 2. Methodological structure (developed by author).

Constructing the simulation model

Three-dimensional modelling of the engine room

The case ship's technical drawings were employed to discern crucial parameters and dimensions. The essential dimensions of the engine room provided in Table 3 were taken in order to model the engine room in 3D dimensions, and the modelling was performed directly in a graphical user interface PyroSim. The model is shown Figure 3.

The engine room spans across three decks, housing diverse machineries and equipment. For clarity in this study, the uppermost engine room deck will be referred to as the "2nd deck," as the "1st deck" (or main deck) lies above the engine room, constituting its ceiling. The 2nd deck accommodates the auxiliary boiler (identified with red colouring of its burner), the Engine Control Room, a workshop area, and a sizable opening at the deck's midpoint, facilitating the operation of the Engine Room crane to maintain machinery (notably the main engine, for tasks like piston or liner replacement). Railings enclose the opening to prevent crew members from falling.

The 3rd deck houses two compressed air reservoirs and the associated air compressors, a cascade tank, and three diesel generators at the aft part of the engine room. The 4th deck features obstructions representing the oily water separator, as well as feed water, lube oil, and fuel pumps. This deck, however, maintains a gap of approximately 1.7 meters from the engine room's bottom deck. Within this space, there exists the shaft connecting the main engine to the propeller, an intermediate bearing for the shaft, a pair of lube oil pumps, and a couple of seawater pumps.

Table 3. The main dimensions of the engine room.

Length	*24 m*
Width	*18 m*
Height	*16 m*
Volume of the engine room	*6912 m^3*
Volume excluding internal obstructions' volume	*6280 m^3*

Furthermore, two staircases equipped with handrails are situated on the portside and starboard side of the engine room. These staircases enable crew members to exit the engine room in case of a fire blocking one side. The first and last steps of each staircase section are marked with a yellow-black pattern as a safety measure, reducing the risk of tripping. Additionally, a small platform exists between the 4th and 3rd decks, adjacent to the main engine. This platform is designated for main engine maintenance, particularly for tasks like scavenge space cleaning.

Parameters setting

Air supply and devices configurations. To collect reliable and precise data on characteristics such as temperature, smoke development and gas dispersion over time, measurement devices were placed across different levels and parts of the engine room. This approach aimed to provide a comprehensive overview that facilitates the comparison of different parameters and their developmental trends.

Consequently, thermocouples, smoke and gas detectors were systematically positioned on every deck, both on the port and starboard sides, as well as on the top of the propulsion plant. A visual depiction of the installation of measuring devices in a 3D view is illustrated in Figure 4, while a 2D view from the right section (aft side of the engine room) is presented in Figure 5.

In Figure 5, a transparency effect was applied to enhance visual clarity. Notably, to prevent overlapping text and ensure improved visual representation, slight

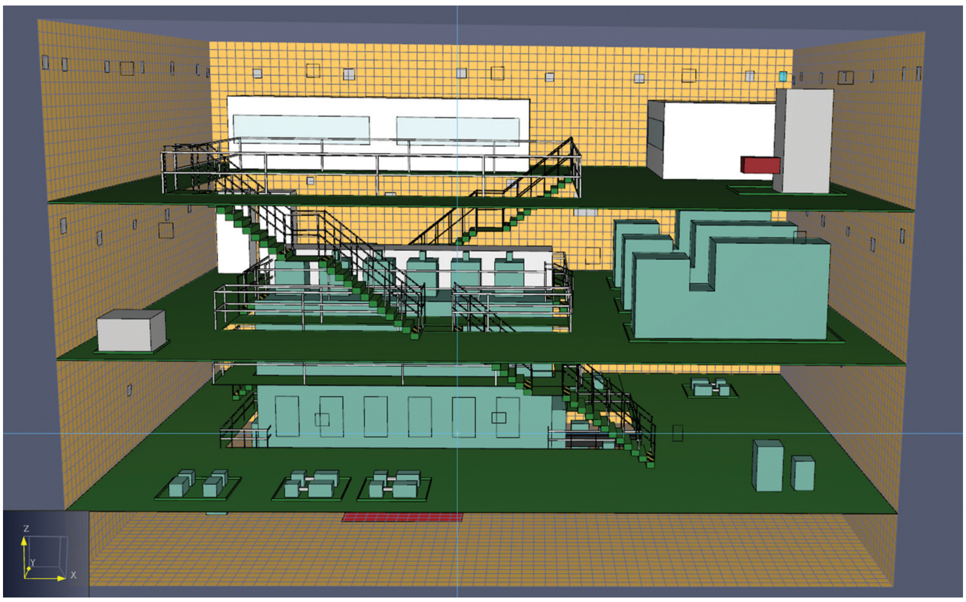

Figure 3. Engine room arrangement.

adjustments were made to the positioning of smoke detectors, even though some devices shared identical x, y, and z coordinates.

The next step in establishing a realistic model involves configuring the ventilation conditions. Detailed examination of the ship's specific drawings revealed the installation of four ventilation fans, of which two are reversible and capable of both supply and exhaust operations. Each fan has an airflow rate of 13.3 m^3/s to ensure sufficient air supply for proper combustion in the main engine, auxiliary engines, and boiler. Under normal operating conditions while the vessel is under the way, two fans work for supply, one for exhaust for continuous air mass circulation and not for exhausting combustion exhaust gases (as they are released through separate exhaust lines outside the engine room, not depicted in the current model). The fourth fan is on standby.

Nevertheless, the distribution of air doesn't occur directly from the fans; instead, an air pipeline system is in place to ensure uniform air distribution throughout the entire engine room. This includes all levels and sections, particularly the areas housing machinery with combustion processes, such as engines and boilers. The vents were strategically placed around the room's perimeter, as demonstrated in Figure 6 for air supply and exhaust. Each vent represents an air sleeve from the ventilation fan distribution system. The vent locations were determined based on technical

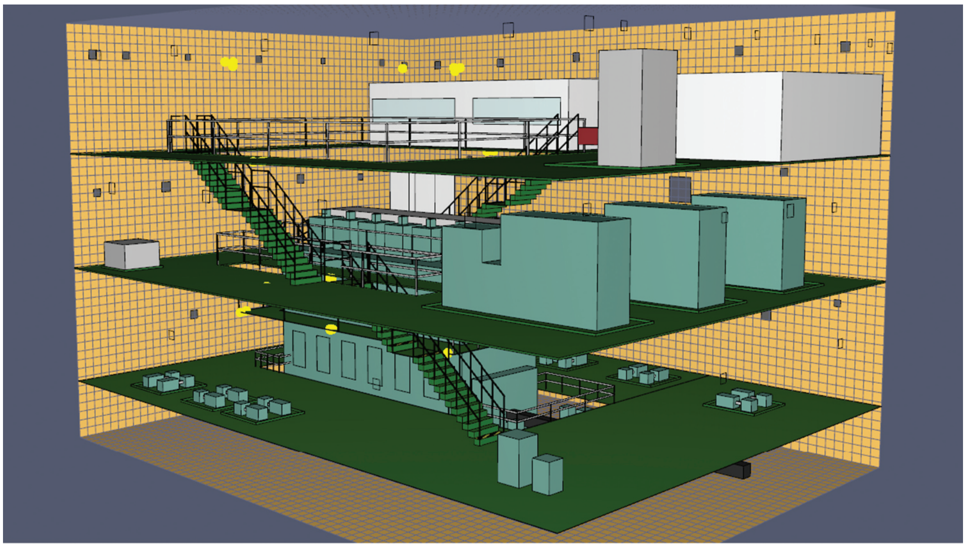

Figure 4. Engine room model with highlighted devices.

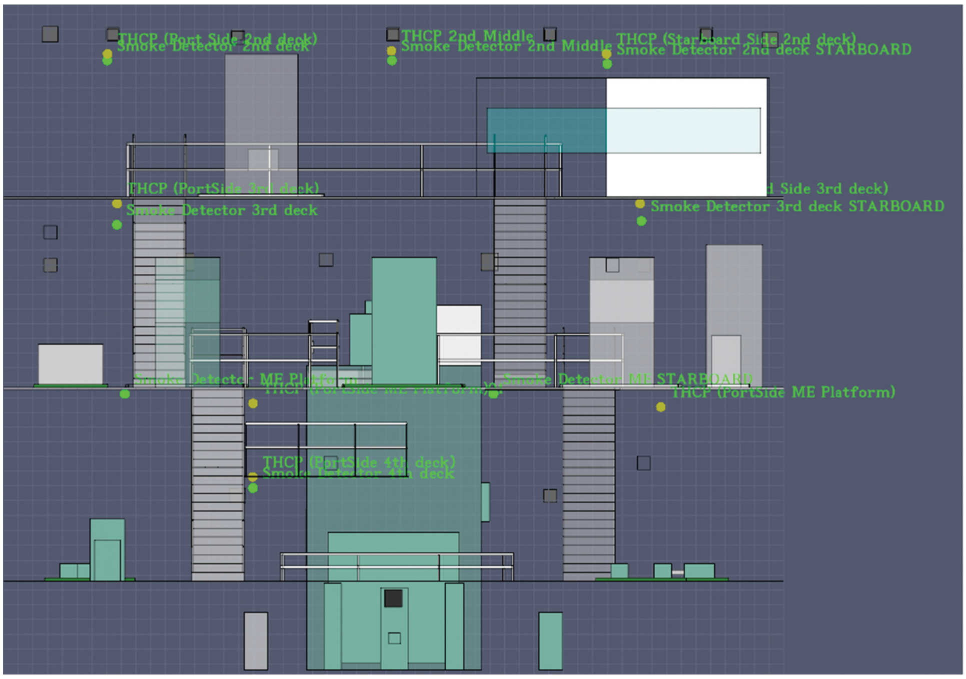

Figure 5. Simulation devices layout.

drawings, though with the assumption of being precisely along the engine room's perimeter, although in reality, they are slightly shifted from the walls toward the centre of the engine room.

Furthermore, a comprehensive analysis of technical drawings facilitated the calculation of the quantity and section area for each vent. The section area varies from 0.0625 m^2 to 0.16 m^2, with one vent presenting a 1 m^2 rectangular for supplying air to the main engine air turbine. Consequently, the total supply rate of 26.6 m^3/s and an exhaust rate of 13.3 m^3/s were established for the model.

Hence, the fire simulations were conducted under the assumption of a continuous air supply and exhaust flow, prior to any measures being implemented to deactivate the ventilation system, whether due to automatic system failure or human factor.

Additional parameters for modelling setup. The simulation duration was chosen as 240 seconds, providing an optimal timeframe to assess the main impact of dispersion and fire on the engine crew and equipment.

To initiate a fire scenario, an 8 m^2 vent was designated on the starboard side adjacent to the main engine, positioned beneath the 4th deck. To establish the needed surface temperature, a value 300 degrees higher than the autoignition temperature

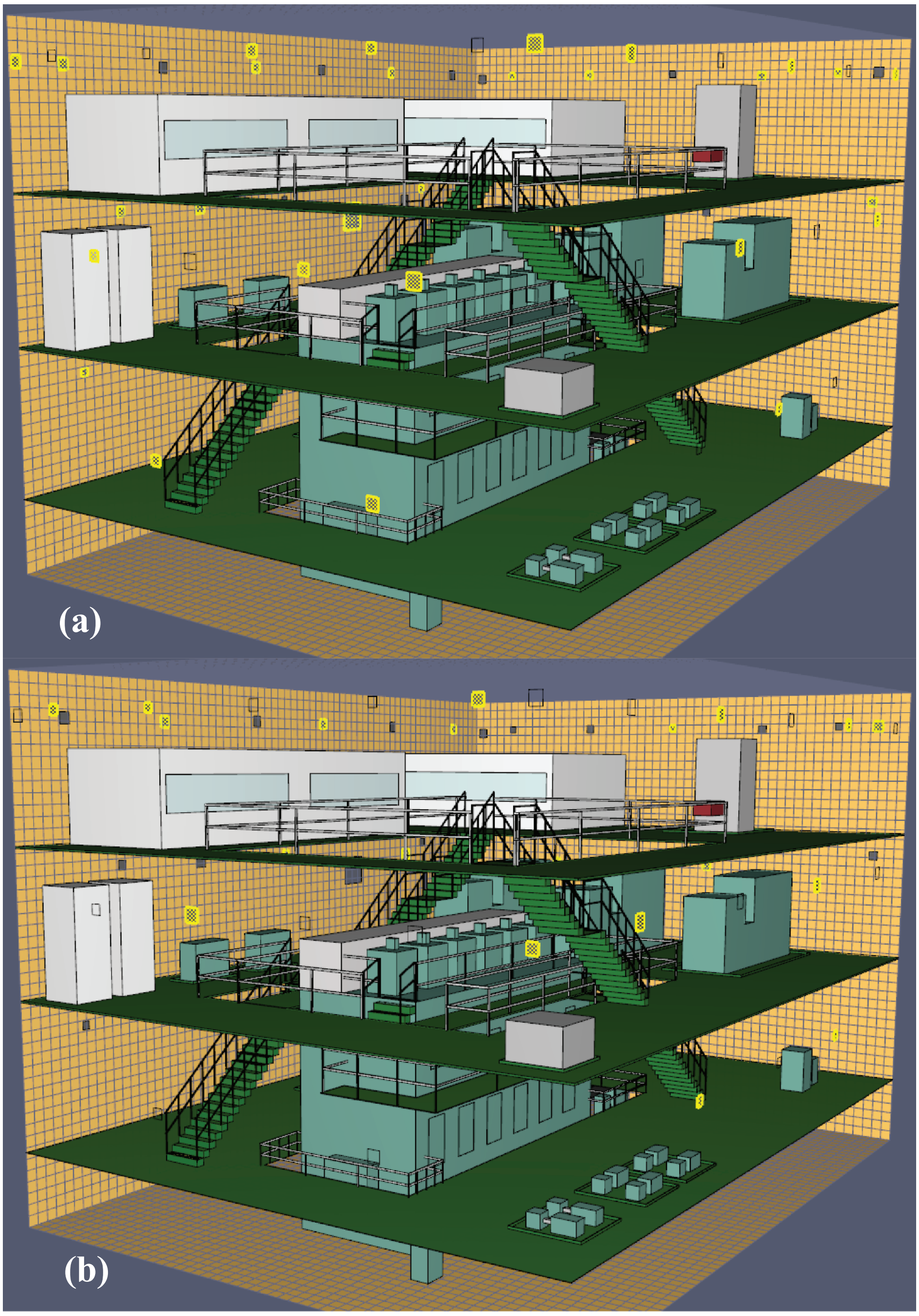

Figure 6. Vents' location for: (a) supply and (b) exhaust.

corresponding to each specific type of reaction was assigned. The default autoignition temperature, set at −273°C, was tailored for individual fuel types based on data from The Engineering ToolBox (2003a).

The ambient temperature within the simulation was configured at 35°C. Notably, the surface temperature of the main engine and two auxiliary engines was set at 80°C, reflecting their operational state assumption. In contrast, the third auxiliary engine's surface temperature was assigned as 70°C to account for its pre-heating condition. Moreover, all obstructions representing steel-made equipment within the engine room were equipped with steel material properties in PyroSim to achieve the most accurate thermal radiation representation.

As highlighted previously, it is essential to maintain a slightly positive pressure within the engine room to ensure an sufficient air supply to the machinery. Consequently, the engine room pressure was configured to be slightly higher than atmospheric pressure outside the engine room, set at 1.05×10^5 Pa.

Lastly, the establishment of an appropriate mesh size is essential to obtaining accurate simulation results. The overall mesh encompassed 108,000 cells, maintaining a uniform cell size ratio of 1.00 across the dimensions of x, y, and z.

Simulations description

The current research will undertake a total of four simulations – two focused on hydrogen as a marine fuel and two involving conventional fuels commonly used in the maritime industry. The initial simulation will analyze hydrogen gas dispersion, while the second will simulate a hydrogen fire scenario. To effectively assess the impacts of these scenarios, it is imperative to compare the obtained parameters with those from fires involving conventional fuels. Hence, the third and fourth simulations will be dedicated to simulating fires fueled by MGO and LPG respectively. The results of these additional simulations can be found in the Appendices.

The critical parameters evaluated in these simulations encompass: the distribution of temperatures and heat release rates across the entire engine room section; the dispersion of oxygen concentrations on various levels and at different time intervals during the fire process; the concentrations of toxic gases such as carbon monoxide and carbon dioxide, which play a pivotal role in fire safety assessment; visibility levels due to the propagation of smoke, a key factor in evacuation scenarios; and the concentration levels of hydrogen during the dispersion simulation scenario will also be a crucial parameter under assessment.

Understanding the permissible limits of the parameters being evaluated is crucial to accurately assessing the severity of the impact caused by a fire. During hydrocarbon fuels combustion, the production of carbon monoxide (CO) and carbon dioxide (CO2) becomes a significant concern when concentrations exceed 35 ppm for CO and 5000 ppm for CO2, as mentioned by the OSHA. In terms of oxygen concentration, OSHA defines an oxygen level of 19.5% as low and potentially hazardous to human health. Additionally, thermal radiation effects play a significant role. As outlined by the Department of Transportation, United States, U.S. Environmental Protection Agency (1989), varying levels of thermal radiation and exposure time can lead to different effects. For instance, exposure to 2 kW/m^2 of thermal radiation within 60 seconds can result a pain, while exposure to 5 kW/m^2 within 60 seconds can cause second-degree burns. Exposure to 10 kW/m^2 within 60 seconds can potentially be lethal. These established thresholds emphasize the importance of considering and understanding these parameters during fire simulations and their potential consequences on human safety.

Hydrogen dispersion. Modelling hydrogen dispersion scenarios within ship engine rooms assumes critical significance due to the transformative potential of hydrogen as a maritime fuel. An in-depth comprehension of hydrogen's behaviour within confined spaces is imperative to ensure the safe and viable integration of this fuel source.

Hydrogen's unique properties, including its wide flammability range spanning from 4% to 75% (The Engineering ToolBox, 2003b), necessitate specialized analysis when introduced to an engine room environment. Given the diversity of machineries and ventilation conditions within this space, these factors can markedly influence the dispersion characteristics of hydrogen in the event of a leak.

Hence, a comprehensive analysis of hydrogen dispersion was indispensable to accurately assess the risks linked to hydrogen storage, handling, and utilization within the engine room. This approach aided in identifying hydrogen's distribution patterns and high concentration zones, apart from the source of leakage. However, the correct modelling of the leakage rate, factoring in hydrogen's physical properties at specific conditions, was vital for precise simulations.

Significantly, the assumption was made that dispersion occurs directly from the gaseous phase, even though hydrogen is stored in a liquid state. In this scenario, hydrogen is regarded in its gaseous form following preheating or depressurization, facilitating its supply to the onboard machinery. This modelling approach permits a comprehensive evaluation of potential hydrogen dispersion behaviours, enhancing our ability to strategize effective safety measures and optimize the utilization of hydrogen as maritime fuel.

Hydrogen fire. Considering hydrogen's remarkably low ignition energy for hydrogen-air mixtures of 0.019 mJ (Kumamoto et al., 2011) and broad flammability range, coupled with the significant fuel volume capacities of marine vessels, the potential for fire occurrence becomes a pertinent concern. Thus, a meticulous quantitative analysis, including fire simulations, becomes imperative to ensure safety. The engine room conditions, with a lot of hot surfaces and powerful ventilation systems, pose heightened challenges in managing hydrogen fires. Employing hydrogen fire scenario modelling is essential in understanding potential hazards and devising effective mitigation strategies.

Simulating hydrogen fire scenarios is a method to comprehend the fire's progression, temperature distribution, and potential risks. The engine room, where hydrogen or other types of fuel are stored, can lead to accidental ignition sources. Accurate simulation offers an understanding of hydrogen fire behaviour and can potentially aid in formulating safety strategies for crew evacuation plans or protecting equipment from severe thermal damage.

In the context of the current model, an assumption was made that hydrogen is initially supplied in its liquid state at cryogenic temperatures. However, upon delivery to the ignition source, it transitions into a gas as temperature increases and subsequently ignites. This modelling approach enables a better understanding of hydrogen's behaviour, facilitating the evaluation of potential risks associated with hydrogen fires in engine rooms.

Results of the simulation and discussion

Hydrogen dispersion

Hydrogen is inherently non-toxic; nevertheless, its high concentrations can pose significant hazards, primarily due to the potential for explosion or fire. There are notable challenges associated with hydrogen. The most critical among these is its flammability range when mixed with air, where as little as 4% hydrogen can result in high flammability. According to guidelines established by OSHA, concentrations exceeding 10 percent are categorized as immediately dangerous. Moreover, hydrogen exhibits a low energy of ignition, implying that even minor sources of ignition like sparks or electrostatic currents arising from pipes and equipment can suffice to ignite the hydrogen-air mixture, leading to potentially perilous fires. Therefore, closely monitoring the hydrogen concentration in the event of a leak is of paramount importance.

In light of these considerations, the present study addresses a specific scenario involving hydrogen leakage. This incident occurs beneath the 4th deck, adjacent to the main engine on the port side bottom deck. The leakage rate of 0.062 m3/s is attributed to a 12 mm hole in a 100 mm diameter pipe. The quantification of this leakage rate was achieved through utilization of the leak rate calculator (Instrumentation and Control, 2023), incorporating essential parameters such as dynamic velocity (8.9×10^{-6} Pa·s), the Ratio of Specific Heats (1.4), and operating under a pressure of 5 bars, corresponding to a hydrogen density of 0.41356 kg/m3. Moreover, a simplified formula sourced from DNV for general flow rate verification can be applied:

$$Q = \frac{1,4 \times d^2 \times \left(\rho_g \times P_g\right)^{\frac{1}{2}}}{\rho_g} = \left[\frac{m^2 \times \left(\frac{kg \times kg \times m}{m^3 \times s^2}\right)^{\frac{1}{2}}}{\frac{kg}{m^3}}\right] = \left[\frac{m^3}{s}\right]$$

Here, Q is the volumetric leakage rate, d defines a diameter of the hole, Pg corresponds to the gas pressure in bar, ρ_g represents a density. The resultant value from this formula closely aligns with the calculated volumetric leakage rate, which corresponds to 0.0256 kg/s of mass flow at these specific conditions of hydrogen density.

To facilitate simulation, a vent with a 1 m^2 area was modeled, incorporating a hydrogen mass rate of 0.0256 kg/(m^2×s), and particle tracers were introduced to visually depict the emission of hydrogen within the engine room.

Figure 7 provides a graphical representation of particle dispersion across all levels of the engine room. This dispersion behavior is primarily influenced by the fact that hydrogen has a lower atomic mass compared to the constituents of air, notably oxygen and nitrogen, which respectively constitute 21% and 78% of the composition. Consequently, hydrogen tends to ascend towards the upper decks due to the convective airflow patterns induced by the supply and exhaust ventilation systems within the engine room. Although hydrogen exhibits an upward mobility tendency, its emission encounters barriers in the form of the decks and staircases integrated into the structural layout. It should be taken into consideration during the design phase because ensuring the swift and effective evacuation from the upper decks becomes crucial in case hydrogen concentration is detected on the lower deck.

Figure 8 presents the data collected by gas detectors placed on each deck, both on the port and starboard sides of the engine room. As previously mentioned, these detectors firstly identify hydrogen presence on the lower decks. In this case, after the occurrence of the leakage event, the gas detectors registered the hydrogen concentration on the 4th deck and the Main Engine platform within 6 and 10 seconds, respectively. Subsequently, with an approximately 30-second delay, the gas detectors recorded hydrogen presence on the 3rd and 2nd decks.

Notably, the dispersion pattern of hydrogen exhibits a "Π" shape distribution from the right view. This means that the dispersion does not predominantly

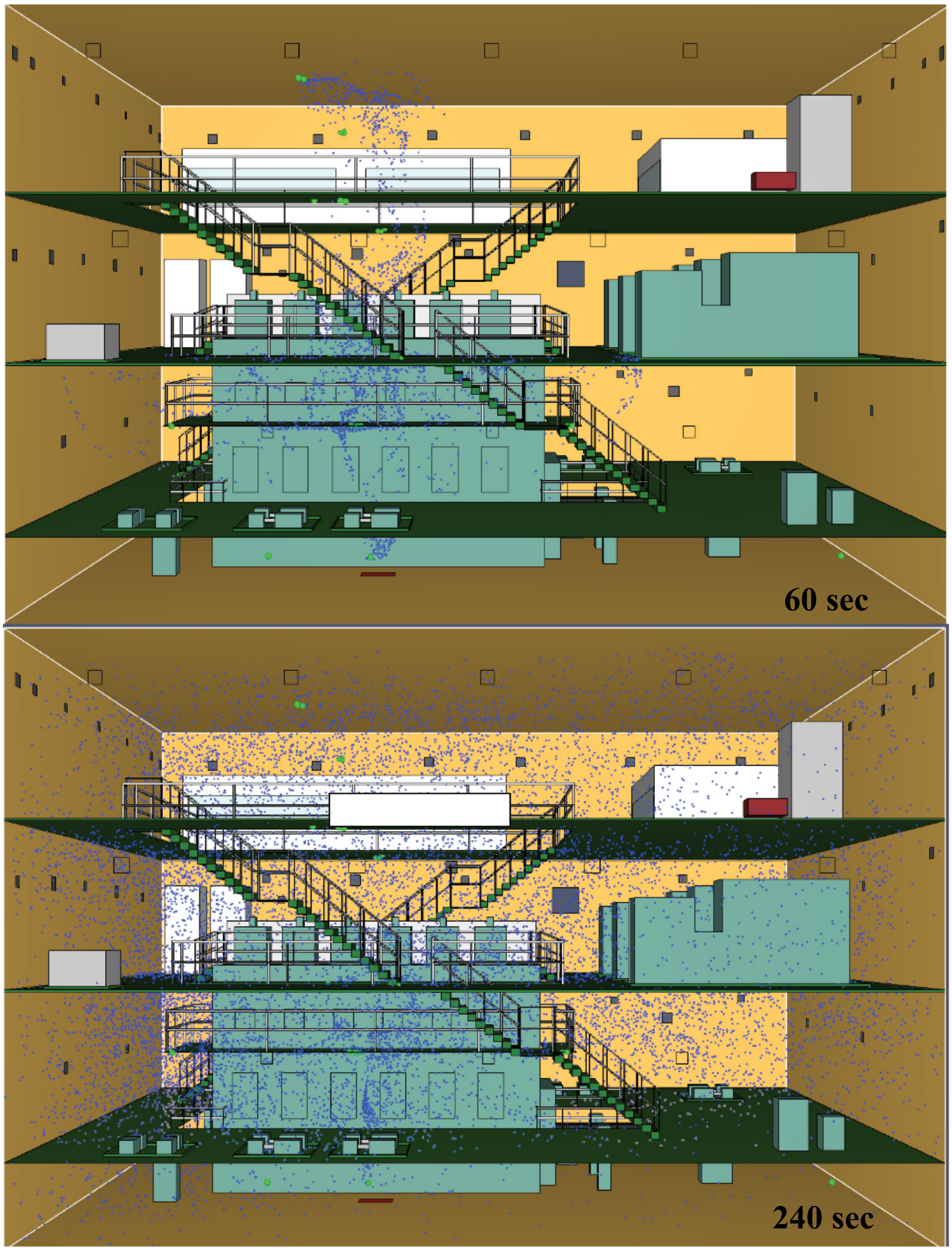

Figure 7. Hydrogen dispersion.

move directly over the Main Engine area from both the aft and forward sections of the engine room. Instead, it follows an upward trajectory, comes into contact with the deckhead, and then descends on the opposite side towards the 4th deck. Consequently, in the event of a hydrogen leakage on the portside, it is advisable to evacuate from the starboard side, given the comparatively longer dispersion time on the former.

Furthermore, it is noteworthy that the hydrogen concentration breaches the 4% threshold twice: initially at the 65th second and again at the 90th second. This concentration level results in the formation of a combustible mixture, making it vulnerable to even the slightest sources of ignition.

Figure 9 presents a more realistic representation of hydrogen concentration within the engine room. It demonstrates that the maximum concentration near the gas leakage source can reach up to 6%. This view underscores the proper placement of gas detectors, confirming their accuracy and closely aligned readings with real values.

In this section, the focus lies in simulating the dispersion of hydrogen, but it is important to clarify that the scenario chosen does not represent the most hazardous condition; nonetheless, it does fall within a range where safety is compromised. The rationale behind this choice is to establish a benchmark for the upper threshold of what can be deemed acceptable. It is crucial to point out that even a minor escalation in either pressure or the hole diameter of the leakage orifice would inevitably lead to severe consequences in terms of the resultant dispersion dynamics. Thus, the current case serves as a prime example of a relatively higher tolerance level in the setting of dispersion scenario. Consequently, in this scenario, there

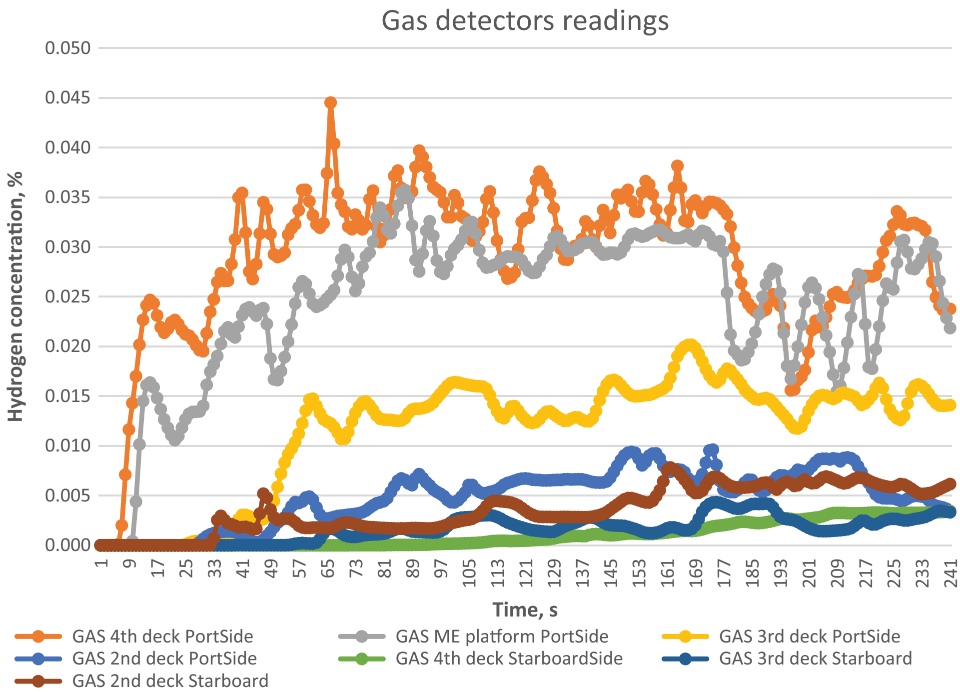

Figure 8. Gas detectors readings.

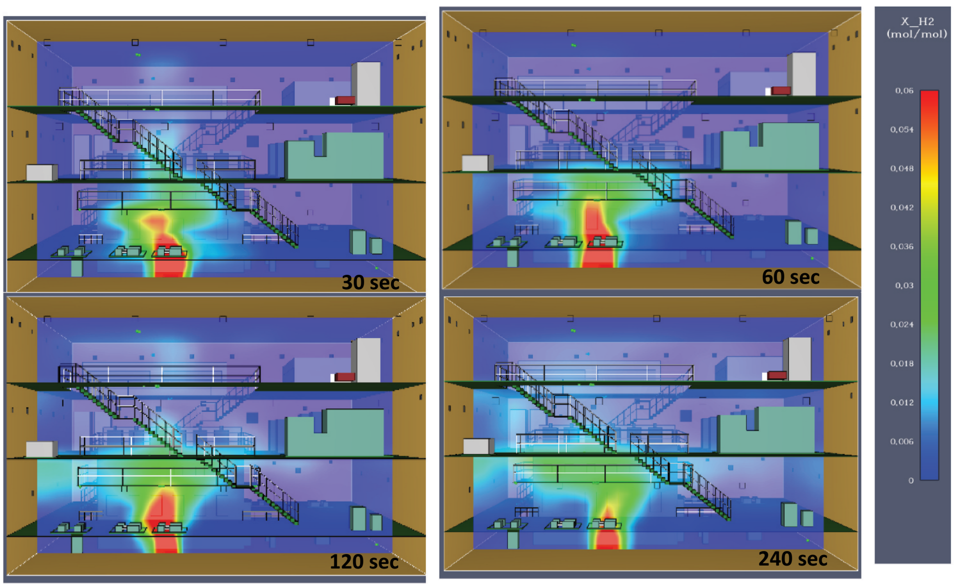

Figure 9. Hydrogen concentration.

remains the potential to implement safety precautions aimed at averting the ignition of hydrogen and the following burning, given that hydrogen concentration fluctuates around the lower explosive limit.

Hydrogen fire

To create a model of a hydrogen fire, certain parameters were adjusted from the hydrogen dispersion scenario. Primarily, considering the hydrogen ignition temperature specified as 500°C within the Fire Suppression section, it follows that the temperature attributed to the burning surface should surpass this point. Nevertheless, empirical simulation observations demonstrated an ignition delay of notable duration, up to 30 seconds, when the difference between the autoignition temperature and the surface temperature is less than 200°C.

Since this section of the study is to analyse fire behaviour only and not to investigate hydrogen dispersion again for the first 30 seconds (which was already reviewed for the whole time exposure in previous section), it was decided to make the surface temperature higher. In this manner, an external factor equivalent to a surplus ignition source, such as a spark or electrical discharge, is simulated to accelerate the fire's rapid ignition. Therefore, the surface temperature was calibrated to 800°C, resulting in a 2-second ignition delay after the initiation of the simulation. During these first 2 seconds, a notable buildup of hydrogen vapor takes place, leading to a significant increase in thermal output, peaking at 45,500 kW (see Figure 10), which can cause the biggest initial hazard on the crew and equipment nearby. At the 11-second mark, there is a comparatively small opposite spike in thermal emission of 14,905 kW. After that, the heat level fluctuates around 26,000 kW until 180 seconds. After 180 seconds, the graph shows the heat going down, and the difference between the lowest and highest heat peaks becomes bigger as the flame becomes less steady.

The reason of fire self-extinguishing can be attributed to the involvement of water vapor, which emerges as a byproduct of hydrogen combustion. During this process, water vapor demonstrates the capability to absorb a considerable quantity of heat as it undergoes evaporation. Upon contact with boundary walls or cooled surfaces, the vapor subsequently undergoes condensation. Importantly, the application of continuous boundary cooling during fire suppression initiates a recurring cycle of heat absorption through evaporation and subsequent heat release through condensation. This cyclic process, rooted in the interplay of evaporation and condensation, has the ability to make a contribution to the gradual deterioration of the fire by gradually diminishing its heat intensity.

Heat release rate and temperature distribution

A similar tendency can be seen in Figure 11 which records the temperature distribution by thermocouples over time. The 2D slice section showcases clear visual representation of fire spreading and its impact on the environment around it. It shows that the first half of the simulation period within the modelling holds utmost significance with regard to potential machinery damage caused by the propagation of fire and elevated flame temperatures. The biggest thermo-impact is applied to the main engine crankcase space, middle of the 4th deck and pumps located nearby. On the second half starting from 120 seconds, there is a gradual decline in temperature levels, which persists until the end of simulation. At this juncture, a nearly uniform temperature distribution pervades the entire engine room.

In Figure 12, it is possible to observe results from the thermocouples from different locations over the entire engine room. These results show that the impact on machinery is somewhat less severe compared to the effects of MGO and LPG fire situations, since hydrogen fire temperature ranges are still lower than what was obtained in simulation scenarios with the other two types of hydrocarbon fuels. In the current simulation, a temperature range of 600–700 °C for 2 minutes on the fourth deck and 400–500 °C for the third deck can lead to serious damage to equipment. Nevertheless, it is also important mentioning that these high temperatures are mostly on the side where the fire started, so other parts of the ship's decks on the other side are affected by more tolerable temperatures.

Oxygen and visibility levels

Hydrogen offers a significant advantage due to its carbon-free nature, positioning it as a clean and environmentally friendly fuel source. Being absent of carbon components, hydrogen combustion yields no carbon emissions, ensuring a carbon-neutral energy option. As a result, hydrogen fires exhibit distinct characteristics that diverge from conventional combustion scenarios. These fires lack carbon-based byproducts and the formation of soot, guaranteeing unobstructed visibility that facilitates quick and efficient evacuation procedures. Therefore, visibility screening is not

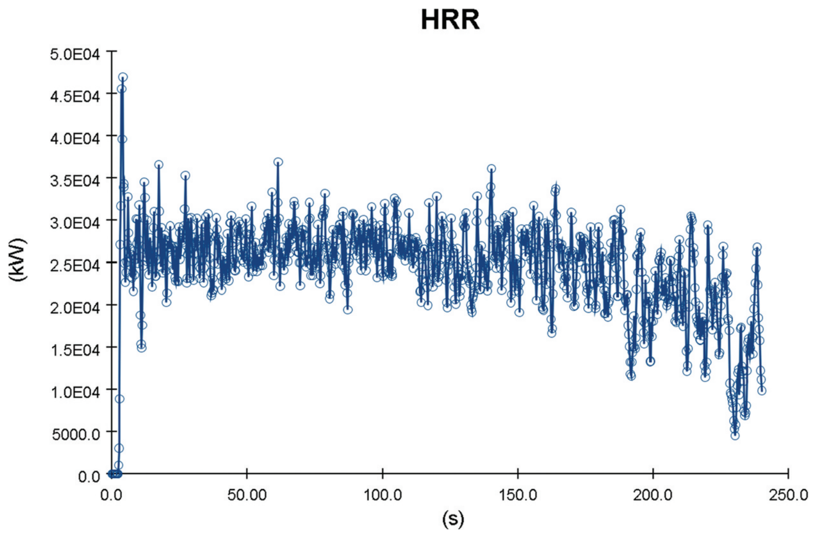

Figure 10. Hydrogen heat release rate.

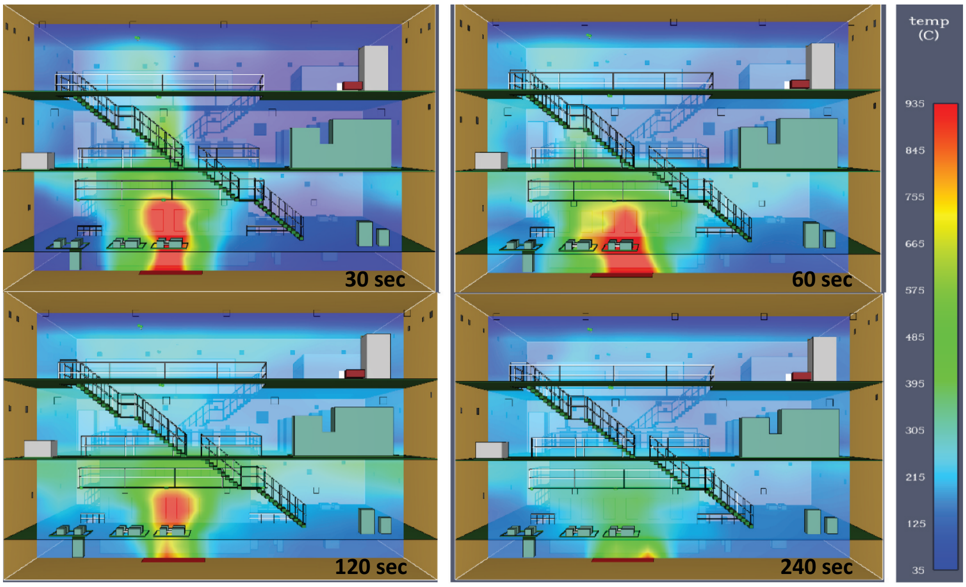

Figure 11. Temperature distribution.

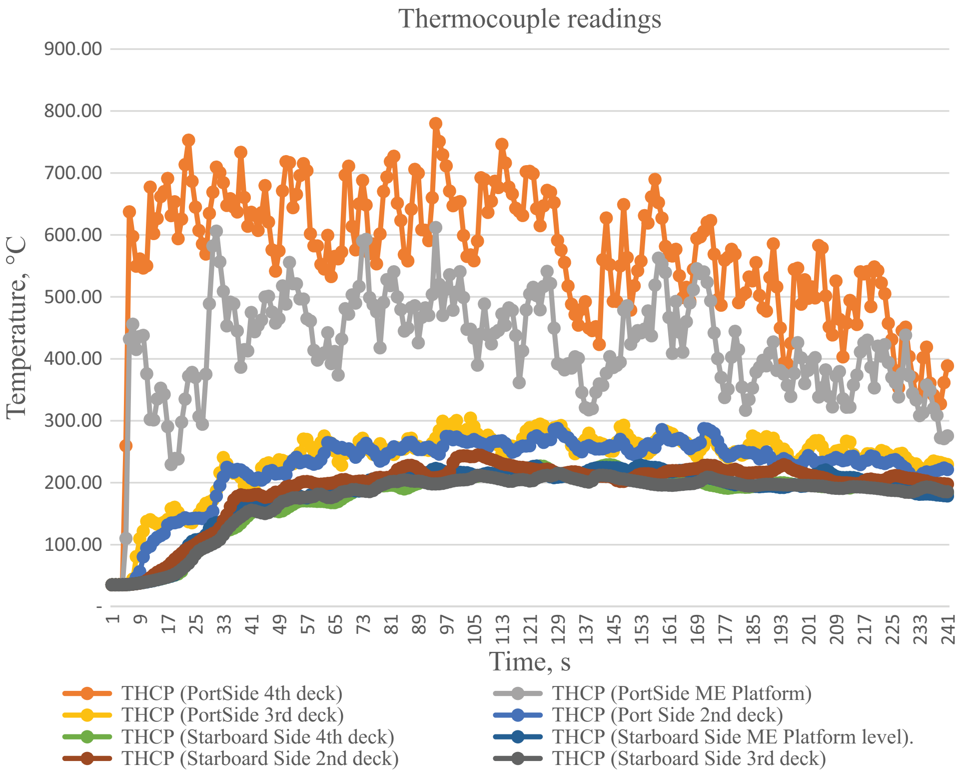

Figure 12. Thermocouples readings.

required in the hydrogen fire simulation scenario, unlike conventional fuels such as MGO and LPG.

Monitoring the oxygen levels throughout the hydrogen fire simulation provides insights into the distribution of oxygen over time. At the outset of the simulation, specifically at the 30-second mark, certain areas in the aft part of the engine room still exhibit an oxygen concentration of approximately 20.5% (see Figure 13). Subsequently, within the following 90 seconds, the region with a lower oxygen concentration progressively expands, encompassing the entire engine room, until reaching a relatively uniform distribution with an average oxygen concentration of around 18.15%.

While this oxygen concentration level is not an immediate trigger for loss of consciousness, it's important to note that oxygen concentrations just below 19.5 % can lead to reductions in both mental and physical performance, as established by OSHA. This performance reduction can significantly impact evacuation procedures. Additionally, a couple of factors contribute to the relatively high oxygen concentration observed during fire simulation. The first factor

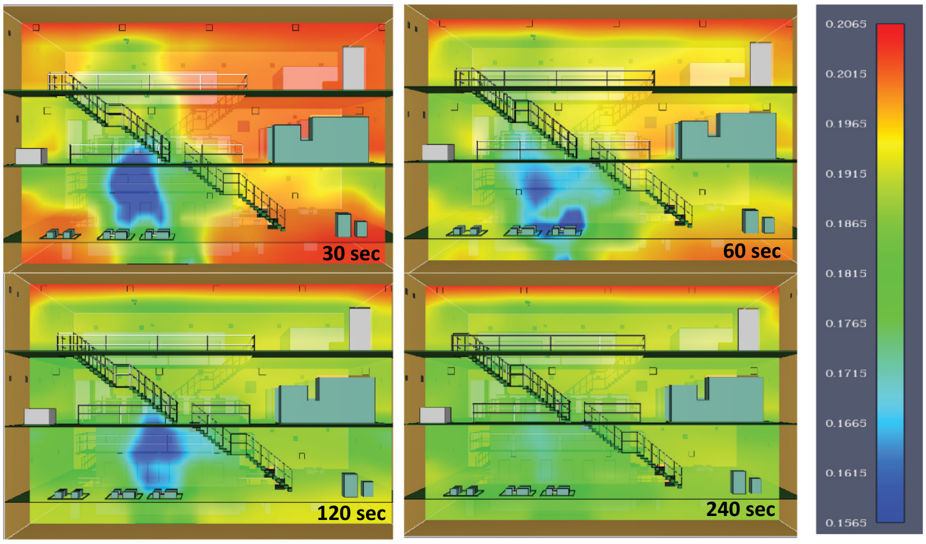

Figure 13. Oxygen concentration.

pertains to the simulation's assumption that the fire occurs while the engine room is operational, with continuous air movement due to functioning supply and exhaust vents. In this scenario, crew members might not immediately shut down all vents right after the fire starts, as real-life situations can involve delays, especially in stressful conditions. The second factor is that the fire persists beyond the 240-second mark in the chosen exposure time, implying that the oxygen concentration will gradually decrease over time.

Findings overview

The flammability range of hydrogen, which indicates the concentration levels at which it can ignite, spans a considerable range from 4% to 75%. This range is notably broader compared to that of substances like MGO and LPG (The Engineering ToolBox, 2003b). This implies that there is a significant variation in the concentrations of hydrogen that could potentially be dangerous.

However, in the event of a leak, the primary concern is to prevent the concentration of hydrogen from reaching its lower explosive limit (LEL). In this context, hydrogen has a slightly higher LEL than MGO and LPG. This indicates that it takes more time for hydrogen concentration in the surrounding air to escalate to a hazardous level, given the same leakage rate. Thus, based on conducted simulations, in the case of a hydrogen leak, there is typically about a minute available to take corrective measures before the risk of explosion becomes significant. The readings from the gas detectors show that the concentration of hydrogen in the air is at a level that could be hazardous, but it's not at a critical point. This is because most of the time, the concentration of hydrogen remains below the threshold of 4%. Therefore, when planning for future construction designs, all factors need to be considered, especially the dimensions of potential leakage points.

For the simulation performed, a hole size of 12 mm was chosen, which corresponds to an area of 114 square millimeters (calculated as$A = \pi \times \left(\frac{d}{2}\right)^2$). This implies that it would be wise to avoid creating excessively large connections between pipes that use gaskets, wherever it is technically feasible. More precisely, designing in a manner where the thickness of the gasket, when multiplied by the circumference of the pipe, does not exceed the maximum allowable area. In the chosen scenario, the circumference of the pipe is 37.7 mm (calculated as$l = \pi \times d$). This implies that the maximum gap between two flanges should not exceed 3 mm, and this gap could be sealed using a gasket. Thus, even if a gasket is partially or fully damaged, the dispersion of substances will not immediately lead to critical concentrations. This precaution ensures that potential leakages remain within manageable levels and do not pose immediate threats.

Regarding fire behavior, the simulations revealed distinct characteristics among different fuel scenarios. In the case of hydrogen fire, the heat release rate displayed a declining trend over time, while MGO and LPG exhibited higher values and relatively stable graphs, with minor fluctuations, throughout the 0 to 240-second exposure period.

Notably, hydrogen, due to its absence of carbon atoms, does not generate carbon dioxide, carbon monoxide, or soot upon combustion. This attribute eases evacuation procedures for the crew, as smoke does not obscure visibility. Conversely, in the MGO fire simulation, the combustion of MGO yielded copious amounts of dense smoke. The proximity smoke detector in this scenario detected smoke within 4 seconds, and all smoke detectors on both sides and all decks registered over 70% smoke concentration after 30 seconds of simulation. The rapid spread of smoke throughout the engine room significantly impaired visibility.

Comparatively, the LPG fire simulation displayed slightly better parameters. Smoke diffusion from an LPG fire occurred at a slower pace, with lesser smoke density, providing better prospects for successful evacuation from the engine room in the event of a fire outbreak.

Despite the fact that the LPG fire simulation showed reduced emissions of CO and CO2 in comparison to MGO (where CO exceeded the standard by five times and CO2 by 4.5 times), the emissions still exceeded the permissible maximum levels established by OSHA for typical conditions. Specifically, CO emissions were 1.5 times higher than the permissible limit, while CO2 emissions were 3.5 times higher than the allowed threshold. A completely distinct scenario unfolded in the case of hydrogen fire simulation, where no carbon emissions were observed.

The average oxygen concentrations at the end of the 240-second simulation differ slightly among the three fire scenarios, hovering around the value of 18% with a variation of approximately ± 0.5%. The slightly elevated concentration can be attributed to the assumption that the fires continued to burn without the air supply being turned off. This assumption aims to mimic a realistic scenario where the air supply is not manually or automatically shut off by the crew, contributing to the slightly higher oxygen concentration in the simulation.

Table 4 simplifies the process of comparing essential parameters across three scenarios by presenting a comprehensive view of the main simulation attributes and various fire scenarios studied in this research.

After conducting a detailed analysis of the extensive data tables obtained from all devices in the modeling results, additional parameters were compared and summarized in Table 4, in addition to the parameters already discussed. One of the PyroSim features utilized for assessment was the fire spread velocity, which enabled the measurement of the rate of fire development. Additionally, the time taken for smoke to propagate to the starboard side of the engine room was evaluated, under the assumption that the evacuation process would primarily occur from the opposite side, which is considered to be more feasible and reliable.

Evacuation time refers to the point in time when it is advisable to leave the engine room, considering that it is based on the assumption that crew members were not affected by the initial thermal wave close to the ignition source during the first few seconds. However, if this advisable time is delayed, the evacuation process could be obstructed by the rapid development of dense smoke at around the 33-second mark for MGO fires and the 37-second mark for LPG fires.

The simulations indicate that hydrogen fires remain hazardous, capable of harming both crew and machinery. However, their potential impact is comparable or potentially even less severe than fires involving MGO and LPG.

Discussion

Perspective on findings

The decision to use Fire Dynamic Simulator for modelling has proven to be an effective instrument of enhancing fire safety assessment in the engine room of a marine vessel. This tool is invaluable for studying different fire behaviours. Nevertheless, this process demands substantial time for designing the model, accurately setting parameters within realistic ranges, and the simulation itself, which can be time-consuming and dependent on computer performance. It is equally vital to assess the simulation outcomes on each stage thoroughly, as disparities may appear, encouraging improvement of model precision and necessitating iterative repetitions of following simulations. Generating plots based on calculated data aids in visually comprehending the numerical outputs, assisting in identifying trends within fluctuations.

Contribution

This project substantially advances the quantitative assessment of hydrogen fires within the maritime sector. The data acquired from 2D cross-sectional views, temperature and gas measurement devices, and visual depictions of smoke propagation can significantly enhance the early-stage construction design of ships, thereby strengthen fire safety plans. The outcomes of this research can serve as compelling evidence for advocating broader hydrogen integration in the maritime domain. It underscores that hydrogen leakage fires, when compared

Table 4. Simulation scenarios comparison.

Parameter	MGO fire	LPG fire	Hydrogen fire
Average Heat release rate	*44 MW*	39 MW	*24 MW*
Average flame temperature of the highest trend	*784 °C*	724 °C	*566 °C*
Fire Spread velocity	*2,85 m/s*	2,85 m/s	*2,45 m/s*
Visibility level in 30 seconds	*4 m*	6 m	*N/A*
Carbon Monoxide emission concentrations	*175 ppm*	50 ppm	*N/A*
Carbon Dioxide emission concentrations	*22500 ppm*	18400 ppm	*N/A*
Oxygen concentration	*17,65 %*	18 %	*18,5 %*
Smoke development time to opposite side	*33 s*	37 s	*N/A*
Evacuation time	*22 s*	23 s	*25 s*

in terms of volume, can be equally safe or even less hazardous than conventional fuels like MGO and LPG.

Conclusion and future work

Conclusion

Firstly, when considering the dispersion of hydrogen gas, it's important to note that there remains a potential for hydrogen to ignite after dispersion. However, the such scenario can be controllable, and safety measures can be taken to manage the situation effectively and prevent fire or explosion, ensuring the safety of both the crew and equipment. Additionally, hydrogen is non-toxic gas and poses no harm to humans through inhalation. The primary hazard in such a scenario lies in the flammability of the hydrogen-air mixture.

Secondly, in the undesirable event of a fire, hydrogen presents a lesser threat to the engine room environment in terms of thermal radiation and temperature distribution compared to conventional fuels like MGO and LPG. Moreover, hydrogen's combustion process has an advantage in not generating smoke, which is in contrast to conventional fuels that produce smoke, hampering evacuation efforts. Additionally, hydrogen's combustion does not result in the production of toxic gases such as carbon monoxide (CO) and carbon dioxide (CO_2), which can be harmful to human health. The absence of toxic emissions during combustion aligns with the goal of minimizing health risks in the event of a fire, further boosting its potential as a safer alternative. This aspect makes hydrogen a promising fuel candidate from a fire safety assessment perspective.

Future work

In future research endeavours, there exists an opportunity to enhance the complexity of the engine room's representation. This could involve the incorporation of finer details such as accurately placed pipelines running along walls and decks, in accordance with technical drawings. Additionally, the integration of a tunnel-type ventilation system could be investigated. Furthermore, the visualization of an emergency escape route, often realized as a vertical duct connecting the lowest deck to the main deck outside the engine room, could provide valuable insights.

The potential influence of extended time exposure on the observed trends in collected data, particularly in response to external factors like the activation of extinguishing systems, needs deeper investigation. Therefore, modelling a simulation that incorporates the activation of a sprinkler system could offer valuable insights into its effectiveness and any associated challenges in firefighting procedure.

The utilization of historical data involving past incidents of fire accidents over recent years can help in estimating the likelihood of fire occurrence within the engine room. This analytical approach could yield insights into the most frequent and predictable fire locations. These could encompass areas adjacent to auxiliary engines, auxiliary boilers where applicable, fuel pumps, and any other locations identified as statistically likely.

Finally, extending the research to include the visualization of the evacuation process through the use of Pathfinder Software could significantly contribute to a comprehensive understanding of crew evacuation procedures. This addition would serve as a valuable tool for evaluating the dynamics and efficacy of evacuation protocols during fire scenarios.

Abbreviations

AIP	approval in principle
ASET	Available Safe Egress Time
BV	Bureau Veritas
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO2	Carbon Dioxide
DNV	Det Norske Veritas
FCR	Fuel Cell Room
FDS	Fire Dynamics Simulator
FDS	Fluid Dynamic Simulator
FSA	Formal Safety Assessment
GH2	Gaseous Hydrogen
H2	Hydrogen
HFO	Heavy Fuel Oil
IC	Internal combustion
IGC	The International Code for the Construction and Equipment of Ships which Carry Liquefied Gases in Bulk
IGF	International Code of Safety for Ships which use Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organisation
LEL	Lower Explosive Limit
LHV	Low Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MGO	Marine Gas Oil
NOx	Nitrogen Oxides
OSHA	Occupational Safety and Health Administration
RSET	Required Safe Egress Time
SOLAS	Safety of Life at Sea
UEL	upper explosive limit

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Byongug Jeong http://orcid.org/0000-0002-8509-5824

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Appendices

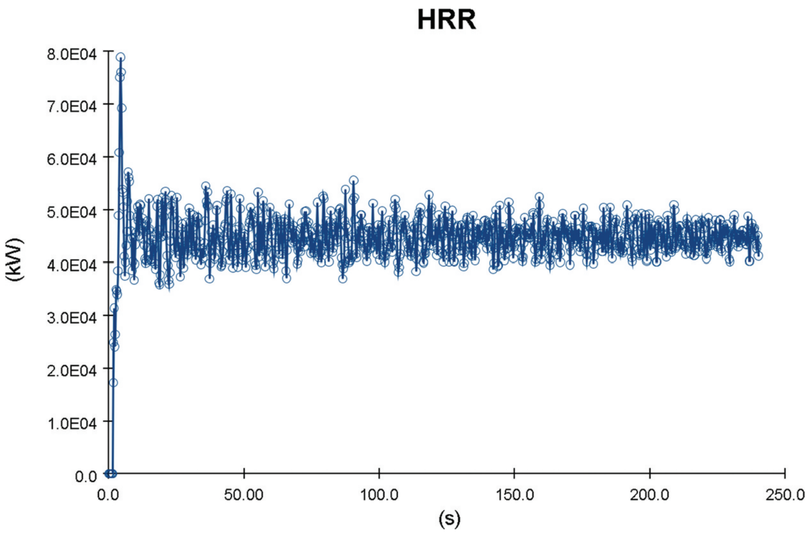

Figure A1. Heat release rate during MGO fire.

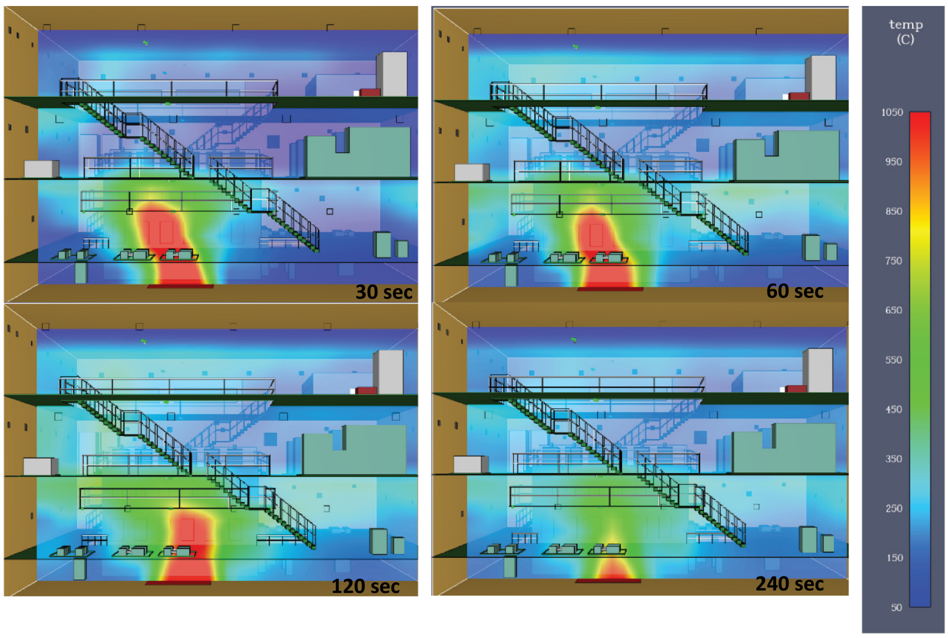

Figure A2. Temperature distribution during MGO fire.

MGO fire

Marine gas oil (MGO) is a prevalent conventional fuel widely used in the maritime industry. Simulating fire scenarios involving MGO is of central importance for comprehending its fire behaviour. The initial step towards configuring an accurate model for MGO fires was to determine the most suitable species that could faithfully represent MGO's characteristics. Following a comprehensive assessment of its key physical properties, n-Dodecane (chemical formula – C12H26) was identified as the closest match. While incorporating Dodecane into Pyrosim, CO and smoke yield values were adopted as 0.012 and 0.038, respectively, as stated in the Fire Protection Handbook by Hurley et al. (2016). The autoignition temperature was set at 220°C based on MGO's safety data sheet from the Kuwait Petroleum Corporation (2012).

The trend of heat release rate over time is visualized in Figure A1, with an average value of approximately 44,565 kW. The heat release rate graph exhibits overall stability with minor deviations, except for a peak at the 5th second immediately after the commencement of the simulation.

The temperature distribution across the entire engine room is illustrated in the 2D slice view presented in Figure A2. This depiction showcases the gradual spreading of hot air from the source of fire throughout the engine room during the simulation period, with temperature concentrations reaching a value of around 450°C beneath the 3rd deck at the end of the simulation.

The visual representation of the quantitative data obtained from the thermocouples placed at various measuring points within the engine room is displayed in Figure A3. Upon examining the provided plot, it is evident that the temperature on the 4th deck exceeds 800°C within the initial 3 minutes of the simulation, posing a significant risk to the structural integrity of steel materials. However, the temperature gradually decreases over time, interspersed with minor fluctuations.

Given that marine gas oil (MGO) is a hydrocarbon-based fuel, the generation of smoke occurs due to the release of carbon during combustion. Owing to MGO's relatively elevated levels of carbon monoxide (CO) and soot yield, the propagation of smoke accelerates rapidly throughout the combustion process. Figure A4 illustrates the progression of smoke generation during the MGO fire at the 10 and 30-second marks of the simulation. This image highlights the challenge posed in identifying a staircase on the starboard side, which becomes increasingly difficult within 30 seconds after the fire's ignition.

While the exhaust vents do contribute to the removal of a portion of the smoke, the overall ventilation system's circulation inadvertently aids in the dispersion of smoke, a trend that persists over time, as demonstrated in Figure A5 Additionally, Figure A5 also indicates a notable interval of 11 seconds between the activation of the first and last smoke detection, further underlining the dynamic nature of smoke behavior during the fire scenario.

Another approach to assess visibility during the fire was plotting 2D visibility slice in order get numerical data representation of visibility in meters. Thus, in Figure A6, it can be seen visibility variates from 1 to 4 meters after 30 seconds of simulation on port side which makes evacuation process to be a challenging.

Furthermore, to evaluate the visibility range from the 4th deck during the MGO fire, a visibility detector was positioned on the initial step of the starboard-side staircase (depicted in Figure A7). Notably, the visibility range experiences a significant reduction, plummeting from an initial 30 meters to merely 4 meters within the first 33 seconds. Subsequently,

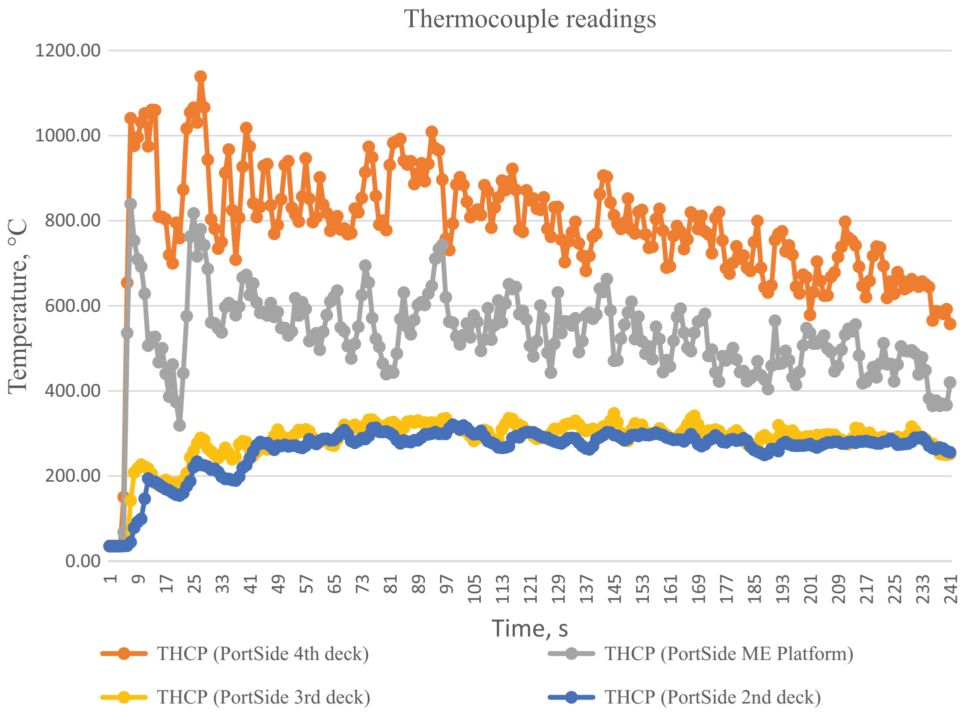

Figure A3. Thermocouple readings during MGO fire.

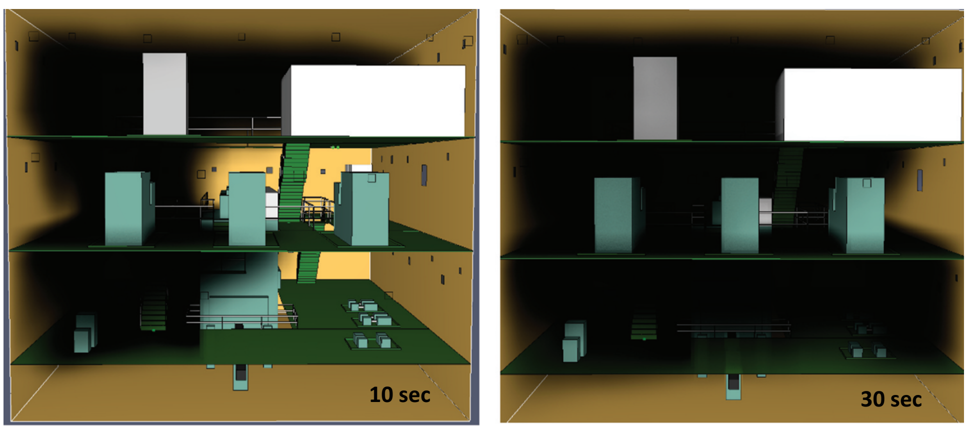

Figure A4. Smoke development during MGO fire.

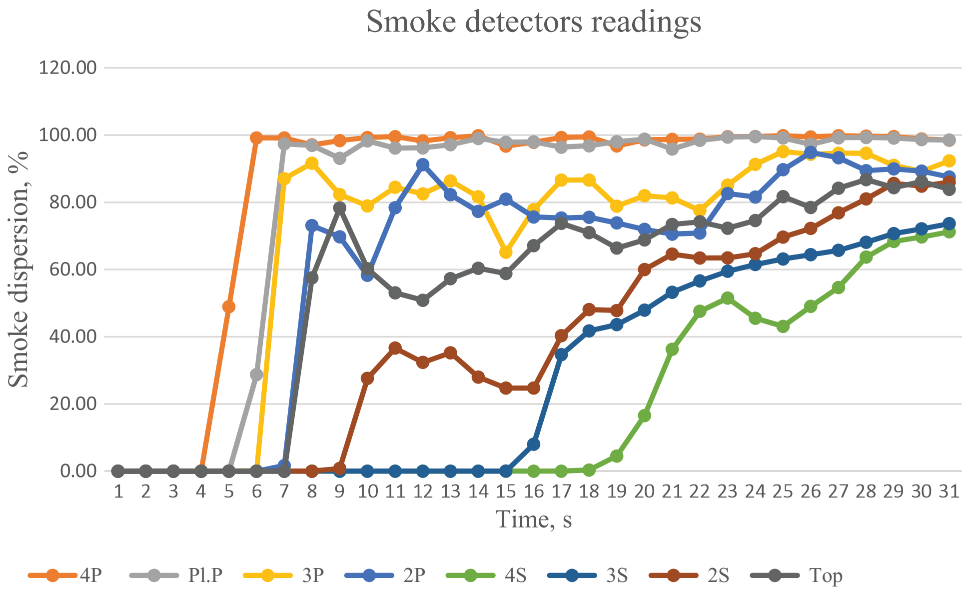

Figure A5. Smoke detectors readings during MGO fire.

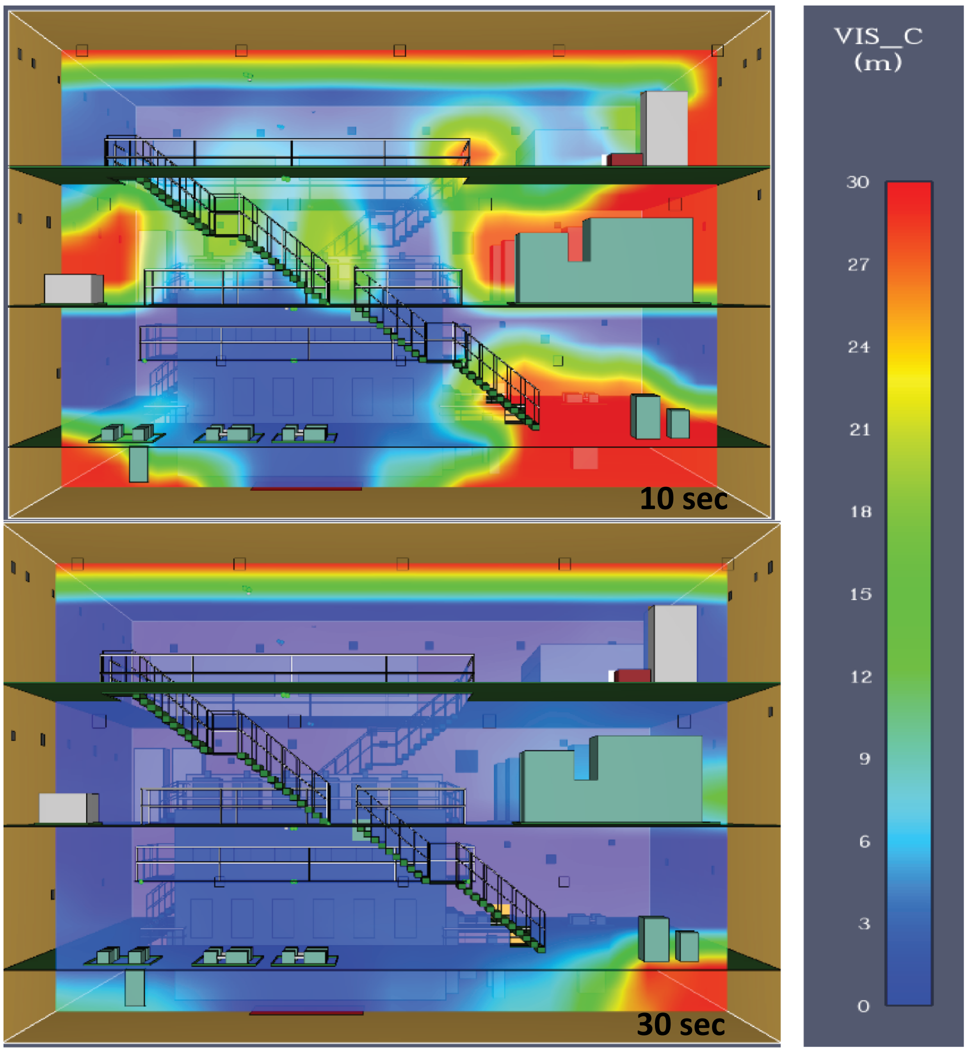

Figure A6. Visibility level during MGO fire.

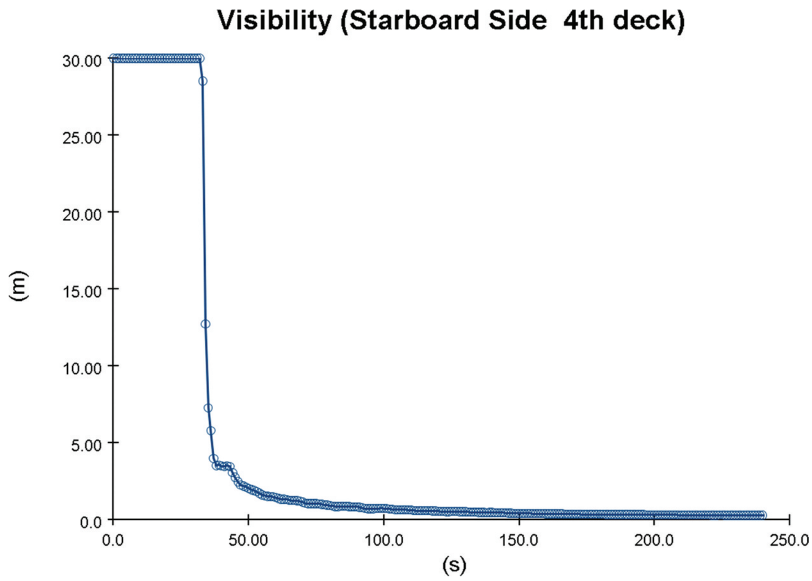

Figure A7. Visibility during MGO fire on 4th deck Strd.

this range continues to decrease and eventually approaches zero as the fire scenario unfolds.

Furthermore, it is crucial to evaluate the formation of toxic gases, specifically carbon monoxide (CO) and carbon dioxide (CO2), during the simulation scenario.

The concentration of carbon monoxide was monitored throughout the combustion process, and it was observed that the concentration reached 175 ppm by the end of the simulation (as shown in Figure A8). According to OSHA standards, a concentration of 400 ppm could be fatal if the exposure time is prolonged over 3 hours. While the CO concentration within the 240-second simulation scenario does not pose an immediate threat of fatality, it still remains a concern for safe evacuation due to its potential to cause dizziness and disorientation.

Interestingly, the observed CO concentration was lower than initially anticipated. It can be attributed to the fact that CO is typically produced more actively in oxygen-deficient environments during combustion (Hurley et al., 2016). However, this is not the case in the current research simulation, as it assumes a continuous air supply to achieve a more realistic scenario prediction. This controlled ventilation condition likely contributed to the observed CO concentration levels.

The distribution of carbon dioxide (CO2) gas was examined, revealing that after 240 seconds of continuous burning,

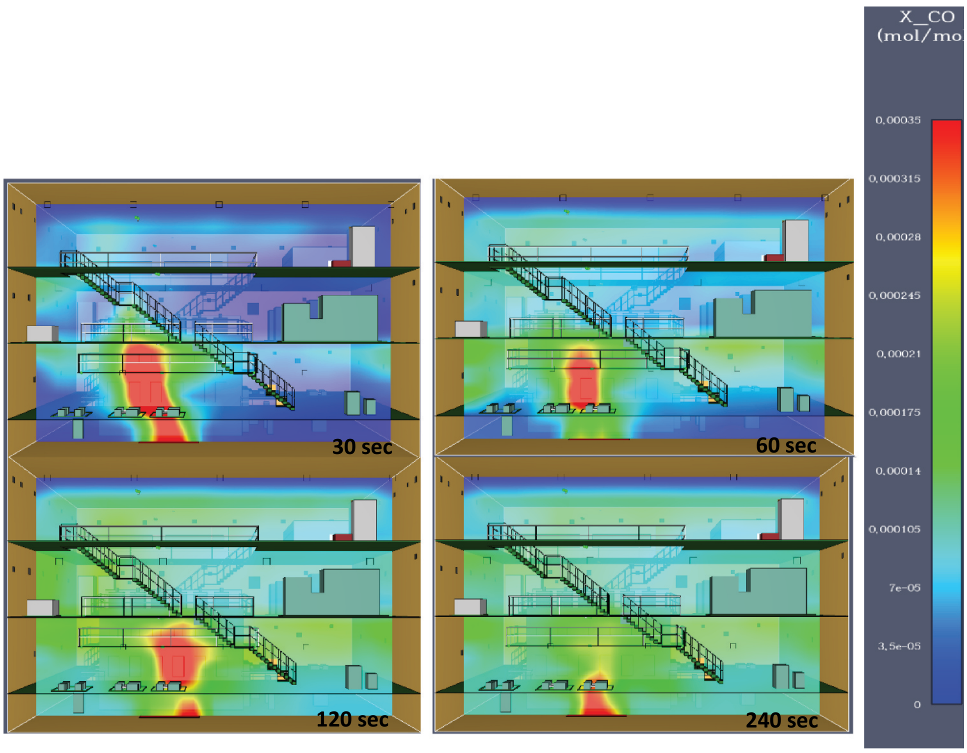

Figure A8. Carbon monoxide concentration during MGO fire.

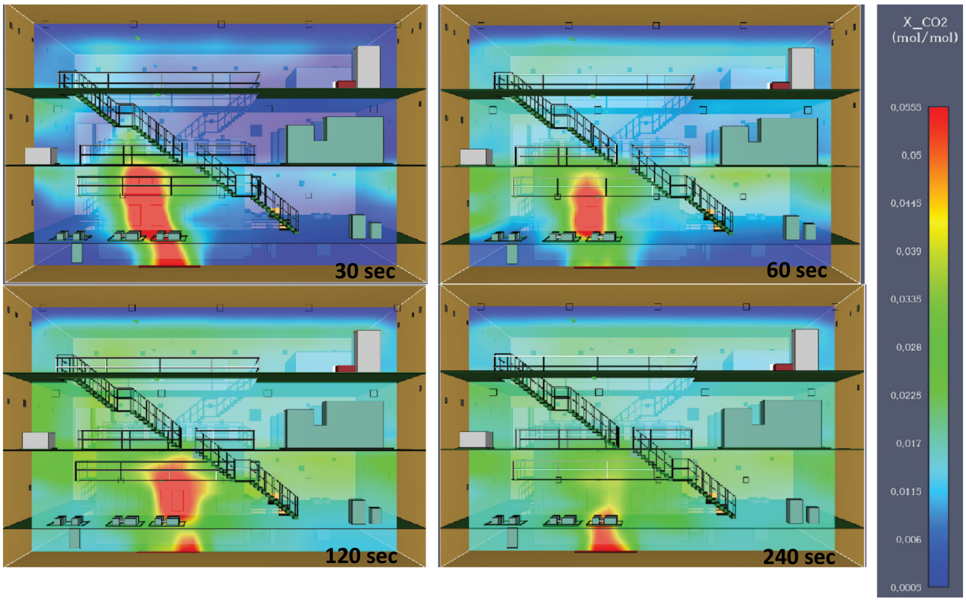

Figure A9. Carbon dioxide concentration during MGO fire.

it constitutes approximately 2.25% of the air within the engine room (as indicated in Figure A9). This concentration corresponds to 22,500 ppm, a level that can potentially impact respiratory function and elevate heart rate, according to OSHA guidelines.

Turning to oxygen concentration, it was observed to gradually decrease throughout the course of the burning process, as depicted in Figure A10 Up to the 60-second mark of the simulation, the oxygen concentration pattern exhibited non-uniform distribution, with relatively normal concentrations at both the lower and upper areas of the engine room. Conversely, the third and fourth decks already displayed signs of oxygen deficiency, registering at around 19% and 18%, respectively.

From the 120-second mark onward and continuing until the end of the simulation at 240 seconds, the oxygen concentration levels became more consistent across the entirety of the engine room, stabilizing at approximately 17.65%. Considering that OSHA recommends a minimum permissible oxygen concentration of 19.5%, it can be deduced that the risk of oxygen deficiency starts to arise approximately 20 seconds after the ignition of the fire

LPG fire

Liquefied petroleum gas (LPG) is a fuel gas which primarily consist of Propane (C_3H_8), butane (C_4H_{10}) in different proportions (Qi et al., 2007). However in this research, LPG was assumed as it consist of Propane only. Therefore, propane was imported to PyroSim as Species. The properties of propane also were taken from the Fire Protection Handbook by Hurley et al. (2016). The autoignition temperature was set as 450°C and CO and smoke yield values were adopted as 0.005 and 0.019, respectively.

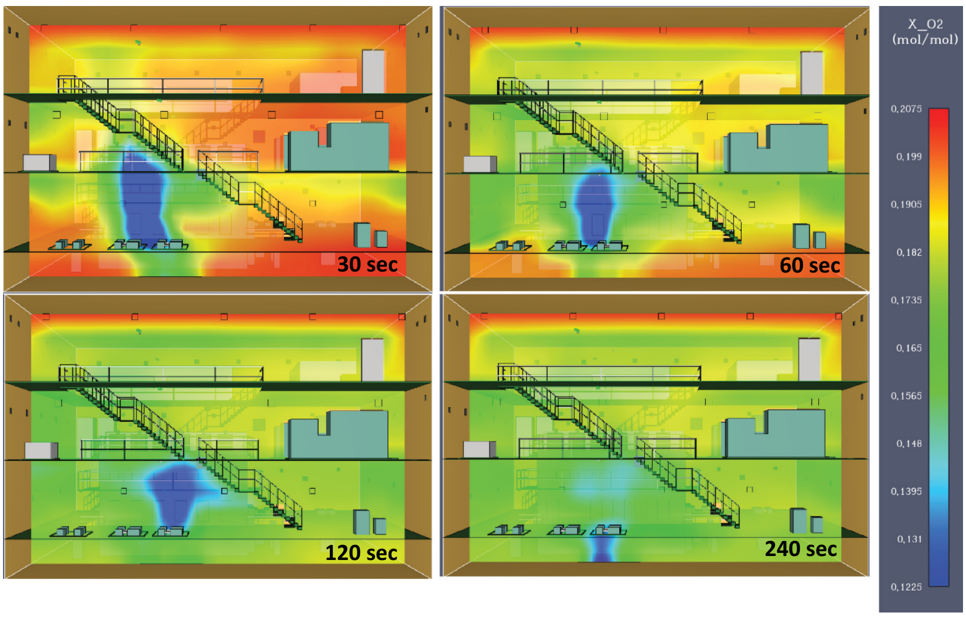

Figure A10. Oxygen concentration during MGO fire.

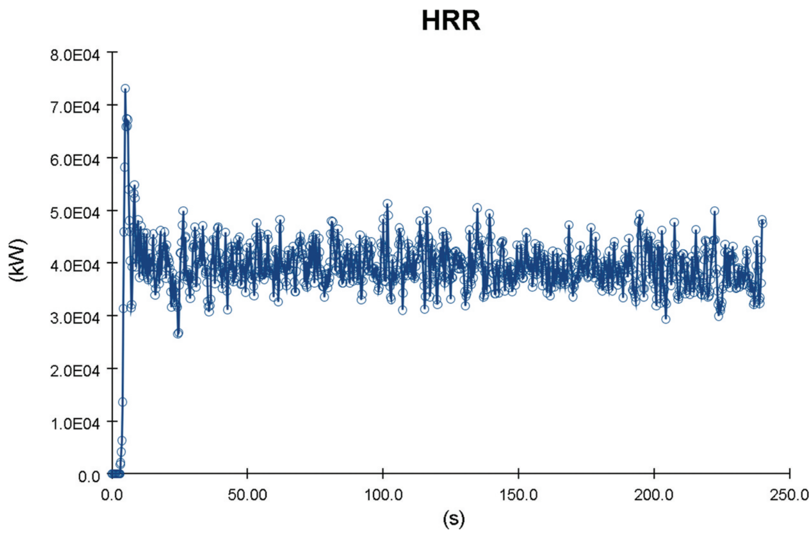

Figure A11. Heat release rate during LPG fire.

Figure A11 depicts the trend of heat release rate over time, with an average value of approximately 38,953 kW. The heat release rate graph also shows overall stability with minor deviations, with the exception of a peak at the simulation beginning.

Figure A12 depicts the temperature distribution across the entire engine room. This illustration depicts the gradual spread of hot air from the source of the fire throughout the engine room during the simulation period, with temperature concentrations reaching around 350°C beneath the third deck at the end of the simulation.

Figure A13 depicts the data collected from thermocouples placed at various measuring locations throughout the engine room. When looking at the graph, it is clear that the temperature on the fourth deck vary around the 800°C mark, with noticeable fluctuations over time. Nonetheless, the temperature begins to fall gradually as time passes.

Similar to MGO smoke development properties, LPG produces it as well, but with less intensity. Figure A14 depicts the progression of smoke generation during the LPG fire simulation at the 10 and 30-second marks. This image emphasises the difficulty of locating a staircase on the starboard side, which becomes increasingly difficult within 30 seconds of the fire's ignition. While the exhaust vents do contribute to the removal of some smoke, the overall ventilation system's circulation inadvertently aids in the dispersion of smoke, as illustrated in Figure A15.

Another method for assessing visibility during the fire was to plot a 2D visibility slice in order to obtain numerical data representing visibility in metres. As shown in Figure A16, visibility varies from 2 to 6 metres after 30 seconds of simulation on the port side, making evacuation difficult.

A visibility detector was also placed on the first step of the starboard-side staircase (shown in Figure A17) to evaluate the visibility range from the 4th deck during the LPG fire. Notably, the visibility range decreases significantly, dropping from 30 metres to 6 metres in the first 40 seconds. As the fire scenario progresses, this range keeps on decreasing and eventually approaches zero.

Similarly to MGO, during the simulation scenario, it is critical to assess the development of harmful gases, notably carbon monoxide (CO) and carbon dioxide (CO2).

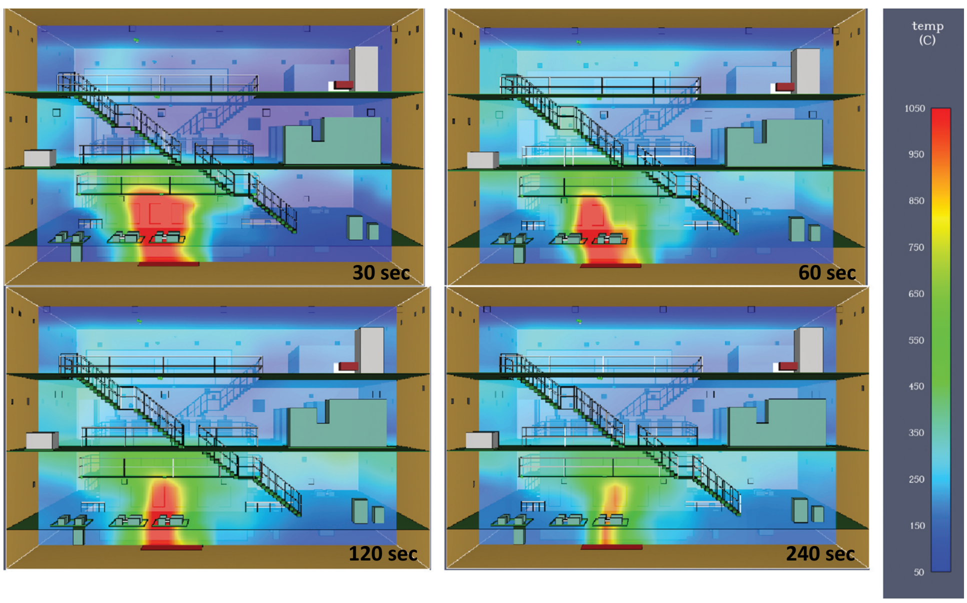

Figure A12. Temperature distribution during LPG fire.

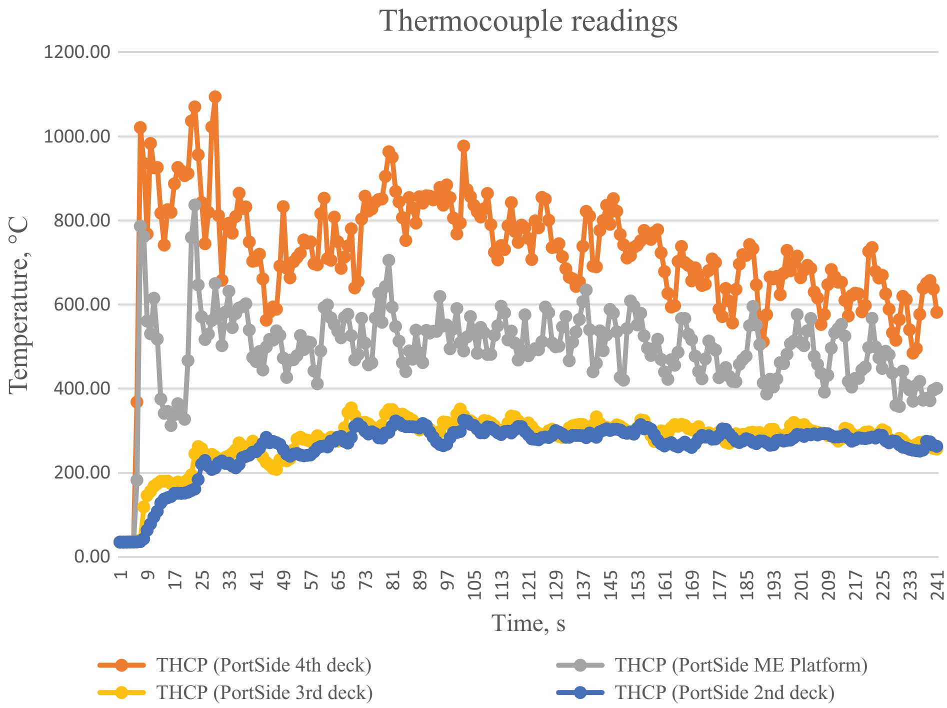

Figure A13. Thermocouple readings during LPG fire.

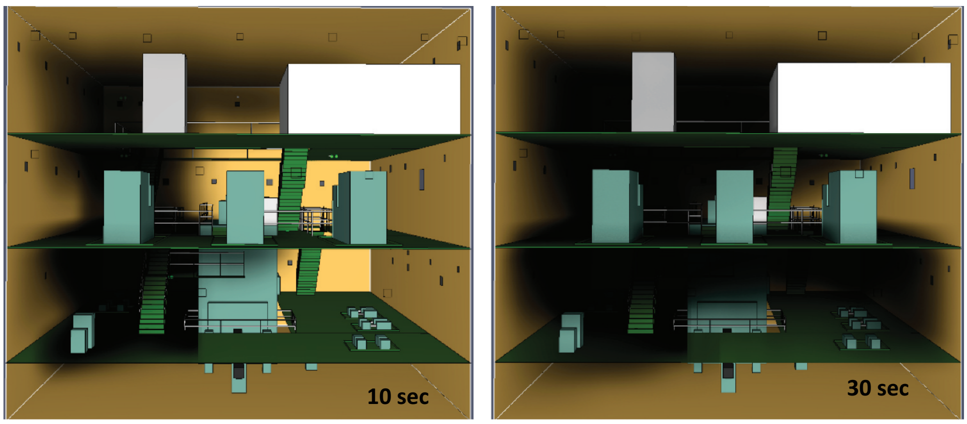

Figure A14. Smoke development during LPG fire.

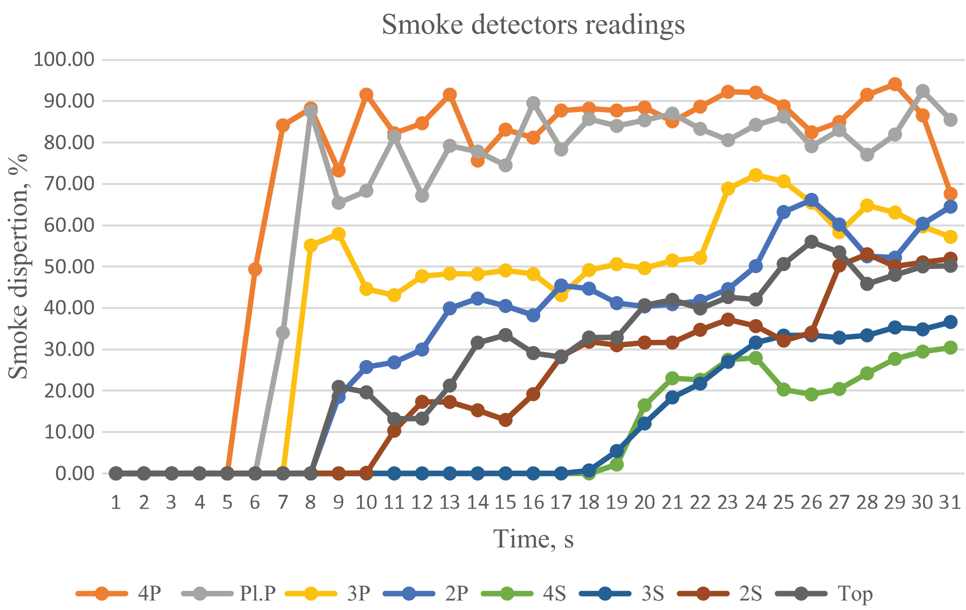

Figure A15. Smoke detectors readings during LPG fire.

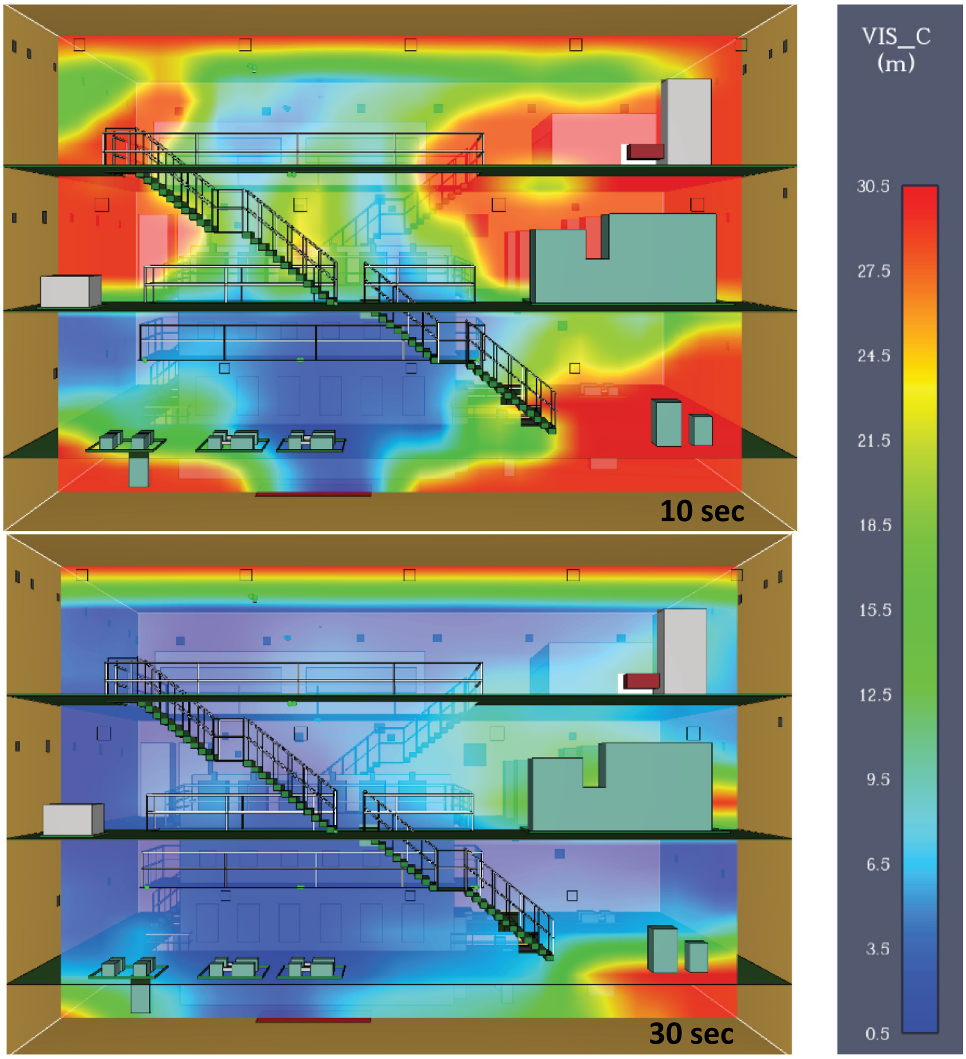

Figure A16. Visibility level during LPG fire.

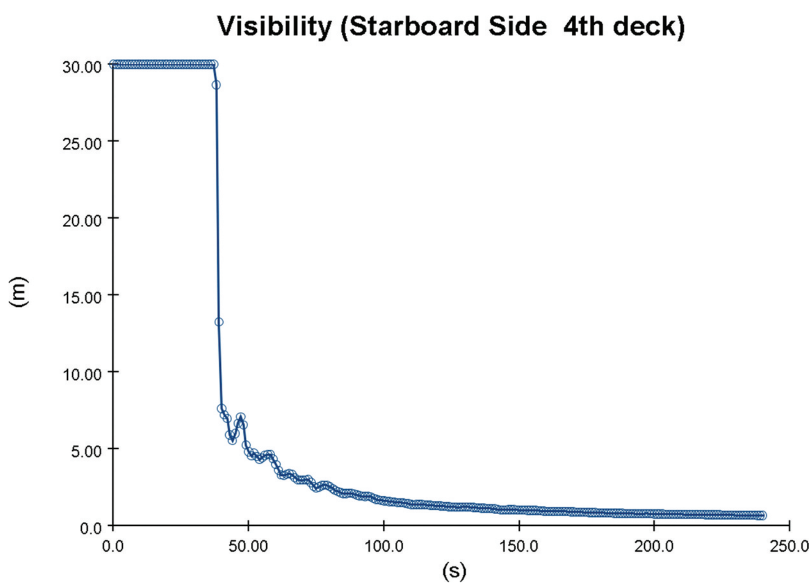

Figure A17. Visibility during LPG fire on 4th deck Strd.

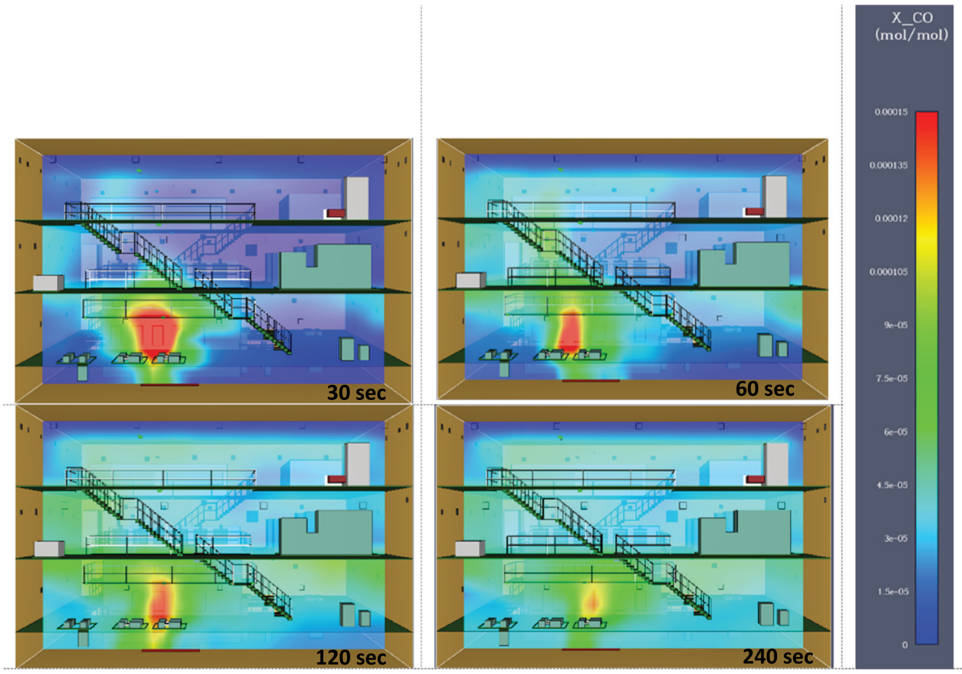

Figure A18. Carbon monoxide concentration during LPG fire.

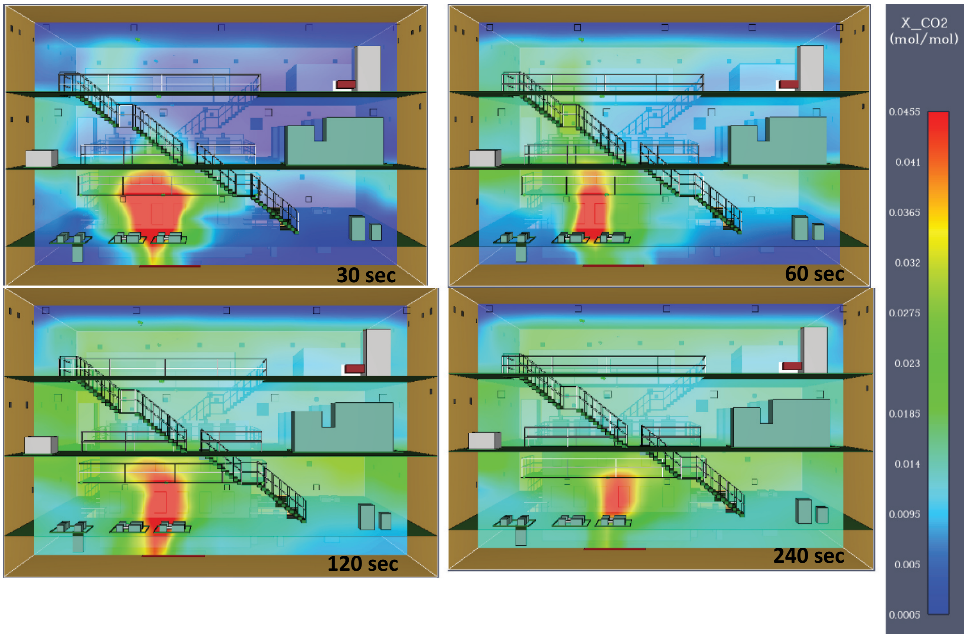

Figure A19. Carbon dioxide concentration during LPG fire.

Carbon monoxide concentration was monitored throughout the combustion process, and it was discovered that it reached 50 ppm by the end of the simulation (as shown in Figure A18). According to OSHA, this value exceeds established standards and can be harmful for humans around.

The distribution of carbon dioxide (CO2) gas was investigated, and it was discovered that after 240 seconds of continuous burning, it accounts for roughly 1.84% of the air within the engine room (as shown in Figure A19). According to OSHA rules, this concentration is also higher than permissible limits.

In terms of oxygen concentration, it was discovered to steadily drop throughout the burning process, as shown in Figure A20 The oxygen concentration pattern was non-uniform up to the 60-second mark of the simulation, with normal concentrations in both the upper and lower levels of the engine room.

From 120 seconds onward, and until the simulation ended at 240 seconds, the oxygen concentration levels grew more uniform throughout the engine room, stabilising at around 18%. Given that OSHA prescribes a minimum allowable oxygen concentration of 19.5%, it was observed that the risk of oxygen deficit begins roughly 52 seconds after the fire is ignited.

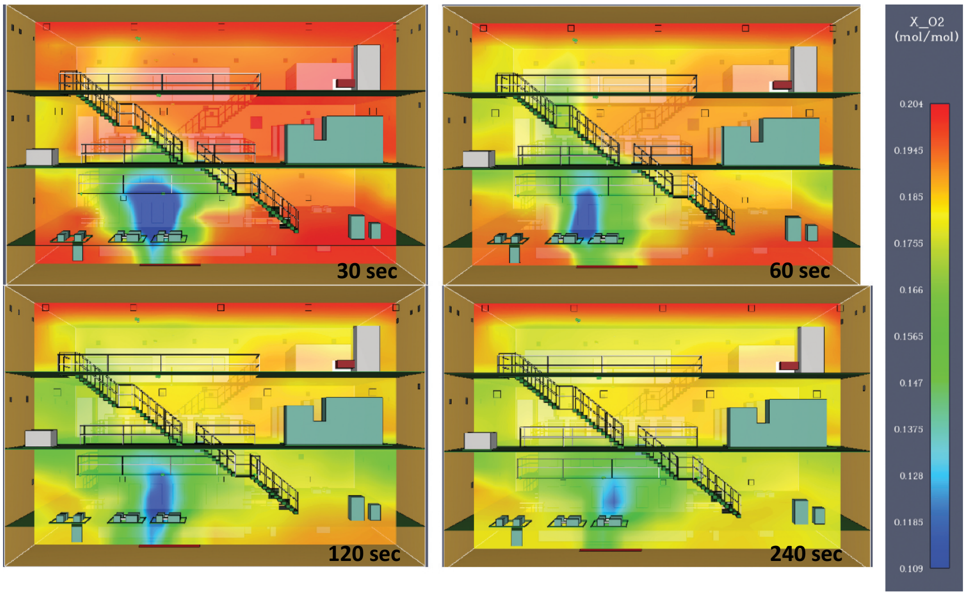

Figure A20. Oxygen concentration during LPG fire.