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Comparative safety assessment of LNG re-liquefaction systems applied on LNG carriers

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ABSTRACT

This research was aimed to evaluate the safety of the LNG cargo compressor room against unwanted gas leakage from two different re-liquefaction systems applicable for an LNG carrier: 1) the Partial (Full) Re-liquefaction System (P(F)RS) and 2) the combination of Partial Re-liquefaction System and Mixed Refrigerant Re-liquefaction system (PRS+MRS). To achieve this goal, quantitative risk assessment was carried out with the integration of system hierarchical modelling, statistical analysis, and CFD simulation. The frequency of initial leakages, occurring to each component of the re-liquefaction systems, was analysed, whereas for the consequence analysis, a CFD program of PyroSim was employed to simulate the gas dispersion in the confined room fitted with mechanical ventilation systems. In addition, various ventilation capacities were investigated with changes in their allocations in the room in order to determine these parametric influences on the results. The risk level of re-liquefaction systems was determined in a quantitative way. Research results clearly presented the importance of the proper arrangement of the ventilation systems. The risk levels were estimated at 5.6 E-3/year for P(F)RS whereas about 9.6 E-3/year for the PRS+MRS in consideration of current regulations. However, the increase in the ventilation capacity was found to reduce the risk levels. The research findings are highly believed to offer meaningful guidance into future safety regulatory frameworks.

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KEYWORDS
LNG re-liquefaction; PRS; MRS; LNG carrier with re-liquefaction system; gas dispersion

Introduction

Background

Liquefied Natural Gas (LNG) is rapidly expanding in terms of energy mix. This fuel trade has increased from 100 million tons in 2000 to nearly 300 million tons in 2017 over the past two decades (Global, 2017). The number of LNG carriers has increased significantly worldwide to carry these large tonnages through waterborne transportation.

LNG is initially extracted as a gaseous energy from the soil or distilled from the refinery and then liquefied to −162°C at atmospheric pressure for the convenience of the storage: its volume is reduced by 600 times when its phase is converted from gas to liquid. In other words, any heat intrusion into the storage tank is likely to contribute to a sharp rise of the LNG temperature, boiling the medium and expanding its volumes, thereby increasing the pressure inside the cargo tanks to a dangerous level.

To avoid any structural damage caused by the overpressure, the safety relief valves can be opened and let the gas be released/lost to the atmosphere or burning the excessive boil off gas (BOG) to the gas combustion unit (GCU) as a fuel source. Both BOG handling options can be considered a waste of energy from the cargo owner's point of view. In this context, over the past decade, the LNG carriers have begun adopting LNG re-liquefaction systems which enable the excessive gas to be re-liquefied and returned to the cargo tank (Cheng & Rahman, 2014; Park, 2019).

Despite the lack of efficiency of the LNG re-liquefaction system in the early stages, vigorous efforts have led those systems to become more attractive and common for ships having gas engines with which the BOG can be re-liquefied and returned to the cargo tanks or consumed for the engines through a fuel gas supply system (FGSS). A recent innovative system applied to a newly built LNG carrier can simultaneously re-liquify and feed the engines, thereby increasing its efficiency as high as commercially feasible.

On the other hand, the current application of those systems has brought about a new safety issue pertaining to the system complexity: the combination of re-liquefaction and FGSS is more likely to cause gas leaks due to the component failures (Pil et al., 2008). In the event of a leak, the gas violently spreads inside the cargo compressor room (CCR) where the LNG re-liquefaction system and the FGSS are placed.

In order to keep the room safe against potential fire/explosion associated with the gas release, the gas concentration in the room should be kept below 5% in the air, corresponding to the Lower Explosive Limit

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(LEL). In this context, a ventilation system acts as a safety device for extracting the gas out of the room. According to the international regulations (IMO, 1998; Scholz, 2016), the ventilation system should be designed with a minimum capacity of 30 times air exchange/hour for the CCR. Due to the brevity of these complex systems, the effectiveness of the current regulations for the ventilation capacity has not been fully tested and verified. This research, therefore, was motivated to investigate the potential risk of these combinations and to evaluate the adequacy or inadequacy of the current design practice and regulations.

Research gap

There have been enriched research projects, publications, and studies aimed primarily at analyzing the issue of gas dispersion, related to the LNG processes in the open environment as well as CCRs and fuel gas preparation rooms (FPR)s.

To begin with, Koopman and Ermak (2007) investigated the gas dispersion phenomena, the vapor burns, and the Rapid Phase Transitions (RPTs) resulting from an LNG spill on the ground onshore or in water, by running Burro and Coyote tests. It was found that the gas dispersion occurring in open environment would be highly uncontrollable.

On the other hand, Rathnayaka (2011) produced a safety assessment in an LNG processing facility with the help of System Hazard Identification Prediction and Prevention (SHIPP) methodology and used safety barriers to give a comprehensive portrayal of the hazardous accidents happening in gas processing facilities. In other words, the authors created this model to prevent the gas release and dispersion, the ignition and the escalation of this phenomenon, which can lead to catastrophic accidents such as explosion.

In response, K.-P. Kim et al. (2011) have performed a CFD analysis for gas dispersion and explosion in a very large crude oil carrier with gas engines. This research underlines the quantity of the potential overpressures as the key risk contributor for gas fueled ships. The concentration of methane inside the FPR was simulated and calculated in a specific period in consideration of various gas leak rates. Furthermore, it was discussed that the ventilation system could play an important role. Further to this study, the explosion inside an FGSS was simulated using Flame Acceleration Simulator (FLACS) which indicated that the impact of explosion is sensitive to gas leakage position and direction.

In the same philosophy, Jeong et al. (2017) put together a quantitative risk assessment of the FGSS for an LNG fueled ship. The authors investigated the explosion impact on the structure of the fuel gas preparation room (FPR). It is worth mentioning that this paper focuses more on the consequences of explosion as an outcome, showing the potential structural damage as an impact of overpressure and not the gas dispersion itself. In addition, the frequency analysis is applied to express the likelihood of initial leak in the FGSS and identify the probabilities of the consequences connected to the scenario of the case study. It was concluded that the high-pressure liquid section of FGSS contributed the most to the damage frequency limit extracted from the frequency analysis.

Finally, this study presents the same facts identified by (K.-P. Kim et al., 2011) that obstacles play an important role in the propagation of the explosion, and the impact of the explosion is serious enough to deform the boundary wall structures. The previous two studies provided feedback on the potential risks of FGSS, but the system did not encompass re-liquefaction systems for LNG carriers.

On the other hand, there is another research done by Lee et al. (2018) who conducted a quantitative risk analysis for gas leak and dispersion in the cargo compressor room of 174 K ME-GI LNG vessels having re-liquefaction equipment. This investigation criticized the brevity of the IGF/IGC codes that only defines the number of gas detectors in the cargo compressor room without specific guidelines on the location as to where to place them, and a CFD analysis for gas dispersion was conducted in order to specify optimum locations for the gas detectors, making suggestions on increasing their quantity.

In addition, Cheng and Rahman (2014) conducted a research quantifying the risk of brittle fracture and the potential consequences of fire in a room with a re-liquefaction plant. The researchers simulated BOG leakage in the Mark III re-liquefaction system to show how brittle the structure would be by measuring the total pressure and temperature distribution. In addition, the combustion model due to leaks was simulated and the volume fraction of methane was measured inside the room. A total of four case simulations were conducted: two for leakage with or without ventilation and two for combustion with high and low air flow inside the plant, where the critical locations for fire/explosion were underlined with methane volume fraction. Those comparative analyses revealed that ventilation would contribute significantly to the avoidance of brittle fracture due to BOG leakage.

In a nutshell, past studies have remarkably addressed accident impacts, hazards, and safety improvements related to the LNG facilities, environment, and the rooms containing FGSS with or without re-liquefaction plant. The past works, however, appear to have some gaps when it comes to the safety of the re-liquefaction system combined with FGSS. Furthermore, concerning the ventilation capacity in the room (T.-W. Kim et al., 2016), no safety evaluation with the ventilation capacity has been made neither qualitatively nor quantitatively.

Motivation

Marine vessels have adopted several systems fulfilling the re-liquefaction process, such as Single Mixed Refrigerant system (SMR), Methane Refrigerant System (MRS), and Partial Reliquefaction System (PRS). The SMR uses propane and/or ethane as a refrigerant and requires an extra propane/ethane storage tank. On the other hand, the PRS and the MRS adopt the Boil-Off closed cycle where those systems use the BOG as refrigerant.

In this context, this research was motivated to conduct a comparative safety assessment for those two re-liquefaction systems applied for an LNG carrier with gas engines. Two credible concepts were proposed: the use of PRS alone but to cover full capacity, expressed as "P(F)RS"; the combination of Methane Refrigerant System and PRS was indicated as "PRS+MRS."

Furthermore, the effectiveness of the ventilation will be evaluated to keep the gas concentration in the CCR low enough, while the possible extent of improving optimal ventilation capacity and arrangement will be determined.

Finally, we will suggest recommendations on design practice for the proposed systems in consideration of the ventilation capacity as a risk control option.

Approaches adopted

This paper generally adopted the IMO's Guidelines for Formal Safety Assessment (FSA; Kontovas et al., 2006) in a quantitative way which was further integrated with the system hierarchical model introduced by Jeong et al. (2018). Figure 1 represents the outline of the overall process.

Scenario analysis

It began with the system modelling for two different re-liquefaction systems: the P(F)RS (Case 1) and the PRS +MRS (Case 2). With the selection of a typical type of LNG carrier, the process diagrams of the corresponding system were designed in accordance with the case ship.

Case ship

To perform a comparative analysis between the P(F)RS and the PRS+MRS, a typical LNG carrier with 173,400 m^3 cargo capacity was selected as a case ship whose specifications can be seen in Table 1.

The two systems were then modelled suitably for the case vessel. Meanwhile, a number of components are constituted in the system at different sizes, design phases, pressures, and temperatures. As a result, the system sections (or components) would be a key parameter to determine the extent of consequences. For example, assuming that a certain system consists of two different sections with different levels of gas pressure, the identical leak scenario can lead to completely different results due to the effect of the pressure: higher pressures lead to higher severity.

Considering these characteristics in the risk assessment, it was necessary to subdivide each re-liquefaction system into subgroups whose risk was individually estimated. Therefore, the combination of the risk of the whole subgroups represents the risk of the overall system. This process modelling has been introduced by Jeong et al. (2018) as a hierarchical system modelling.

Partial (full) re-liquefaction system

Figure 2 shows the hierarchical modelling for the P(F)RS system, which is divided into 21 subgroups in consideration of fuel phase, temperature, pressure, and pipe size.

According to the ship specification, the BOG produced from the cargo tanks is estimated at 3,450 kg/h at 18 knots of service speed. Of the total, 683 kg/h is subject to re-liquefaction and the remainder of 2,767 kg/h is consumed by the gas engines.

For the P(F)RS, 3,450 kg/h of BOG at −120°C and 0.14 bar runs off the cargo tank and passes through the cold line of the heat exchanger and continues to the suction of the five-stage high-pressure (HP) compressor unit at 0°C and 0.1 bar. After the second stage of the compressor unit, 600 kg/h of gas is supplied to the generator gas engines at 43°C and 6 bar. At the outlet of the fifth stage, 2,167 kg/h of gas is supplied to the main gas engine at 40°C and 305 bar, while in parallel 683 kg/h enters the hot line of the heat recovery unit at 41°C and 294 bar in order to absorb heat from the aforementioned cold line.

Moreover, the gas exits the heat recovery unit at −107°C and 294 bar, being ready to flow through the Joule-Thomson (J-T) valves. During this stage, the gas is affected by the J-T effect through which the pressure and the temperature drops dramatically to 4.1 bar and −139°C. In this state, the gas encounters a critical phase transition from gas to liquid and enters the liquid/gas separator. Inside this, the final component, methane turns into liquid and the last traces of gas return to the inlet of the direct contact heat exchange (DCHE). Right before returning back to the cargo tanks, the liquid passes by a set of valves, so that the safety pressure for the tanks can be kept as low as 0.14 bar.

Partial re-liquefaction system+methane refrigerant system

As shown in Figure 3, the PRS+MRS system differs from P(F)RS by adding closed-refrigeration cycles using methane as refrigerant. Based on the P(F)RS, the PRS

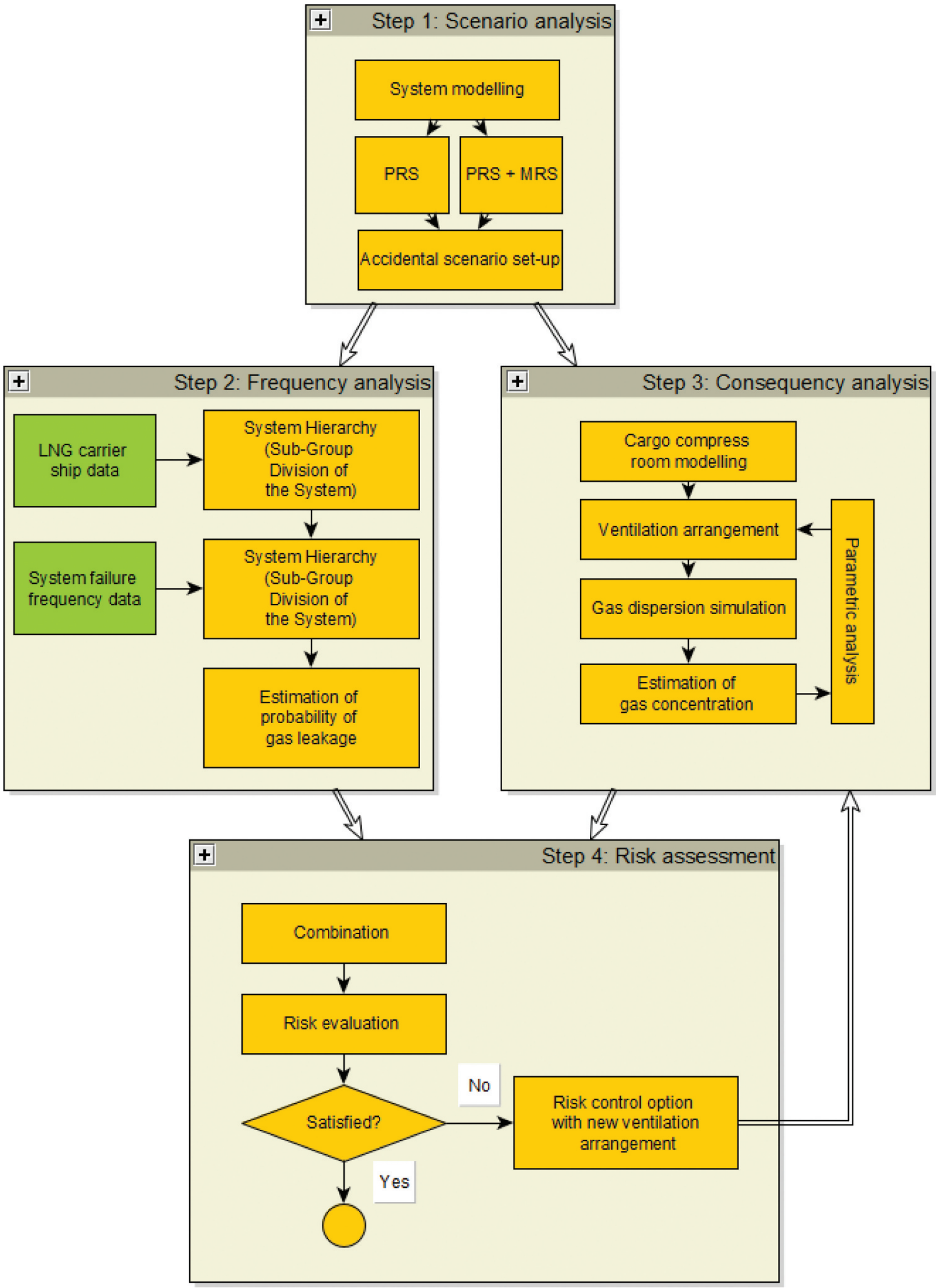

Figure 1. Outline of quantitative risk assessment.

Table 1. General specifications of the case ship (CHIOS, 2020).

Items	Specifications
$L_{BP} \times B \times D$	288.5 m × 46.4 m × 26.5 m
Capacity	173,400 m^3
Main Engine	MAN B&W 5G70 ME-C9.5-GI-TII × 2 sets
MCR	12,590 kW × 69.1 rpm, each
NCR	10.700 kW × 69.1 rpm, each
BOG Consumption	66.408 t/day or 154.438 m^3/day (LNG density: 430 kg/m^3)
Equivalent HFO consumption	77.218 t/day
BOR at 18 knots	0.094

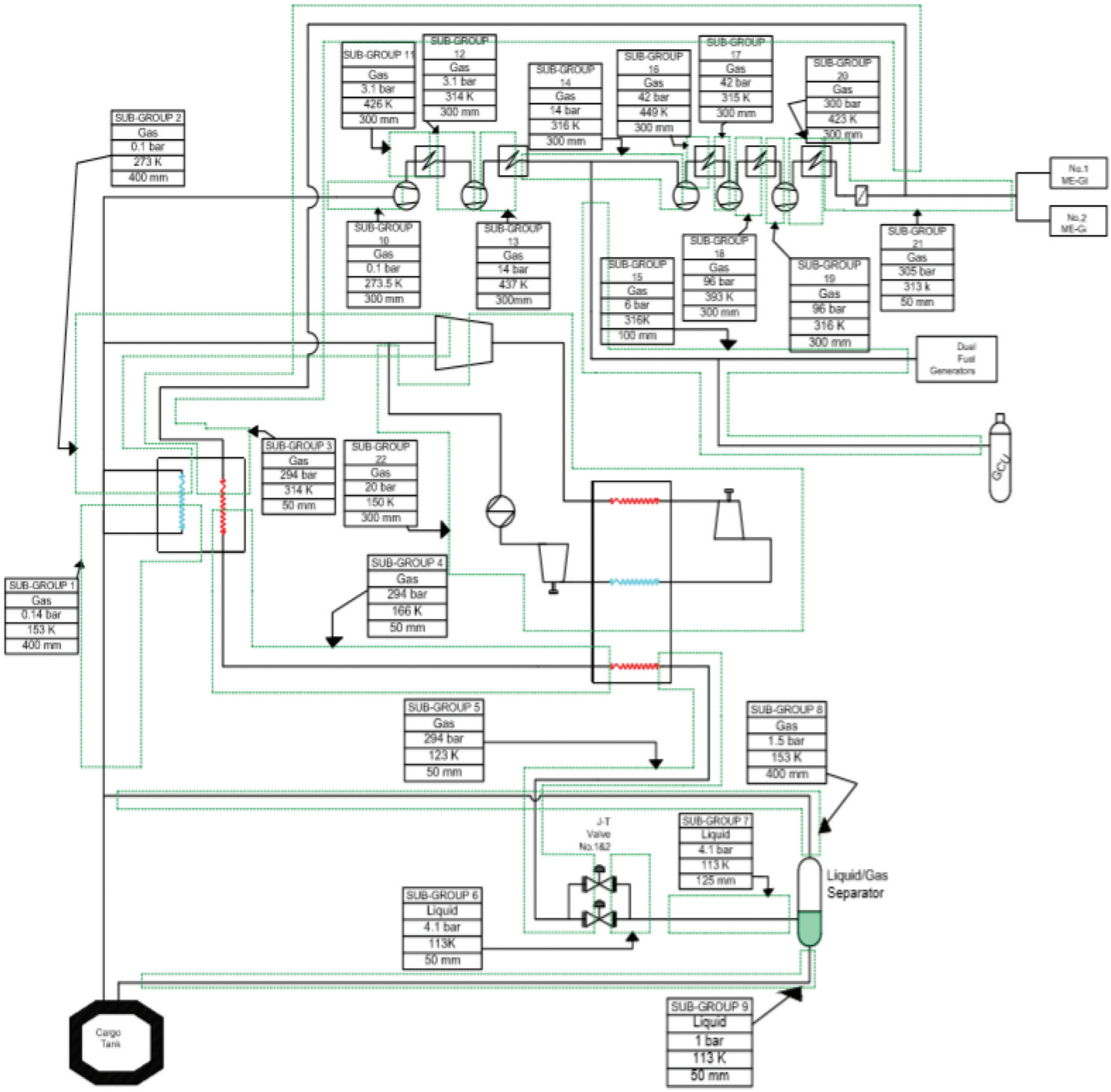

Figure 2. P(F)RS GA subgroup division.

+MRS has an additional refrigeration plant which consists of a Methane Refrigerant (MR) compressor, a second heat recovery unit, an expander, a compressor, and a cooler.

The BOG production and the engine consumptions are the same as the P(F)RS. The properties of the BOG passing through the components remain unchanged, except from the inlet and outlet of J-T valves due to the refrigeration plant which increases the coefficient of performance (COP) and the refrigeration capacity of the system. As a result, the methane outlet in the J-T valve becomes a liquid status.

While the description of the common parts with the P(F)RS is not disregarded, the operation of the MR cycle will be discussed. The amount of methane is compressed via the MR Compressor and transferred through the hot line of No. 2 DCH where it is cooled from the counter flow of the stream after the expander. The expander is connected to the compressor for system's energy saving and after the cold line, the cold gas passes through the compressor and the cooler in order to be supplied again to the MR Compressor. As far as the outlet of the No. 1 DCHE's hot line is concerned, the gas exits at 294 bar and −107°C. After that, it heads to the second hot line of the No. 2 DCHE where it is cooled to – 150°C at the same pressure. The next stage is to insert the J-T Valves where the pressure increases to 4.1 bar and the temperature decreases to −160°C. The gas is turned into liquid and enters the liquid/gas separator to split the last traces of gas from this liquid. Again, the liquid at 1 bar passes through a set of valves to reduce its pressure down to 0.14 bar before returning to the cargo tanks. In addition, the same amount of gas from the top of the separator returns to the inlet of No. 1 DCHE.

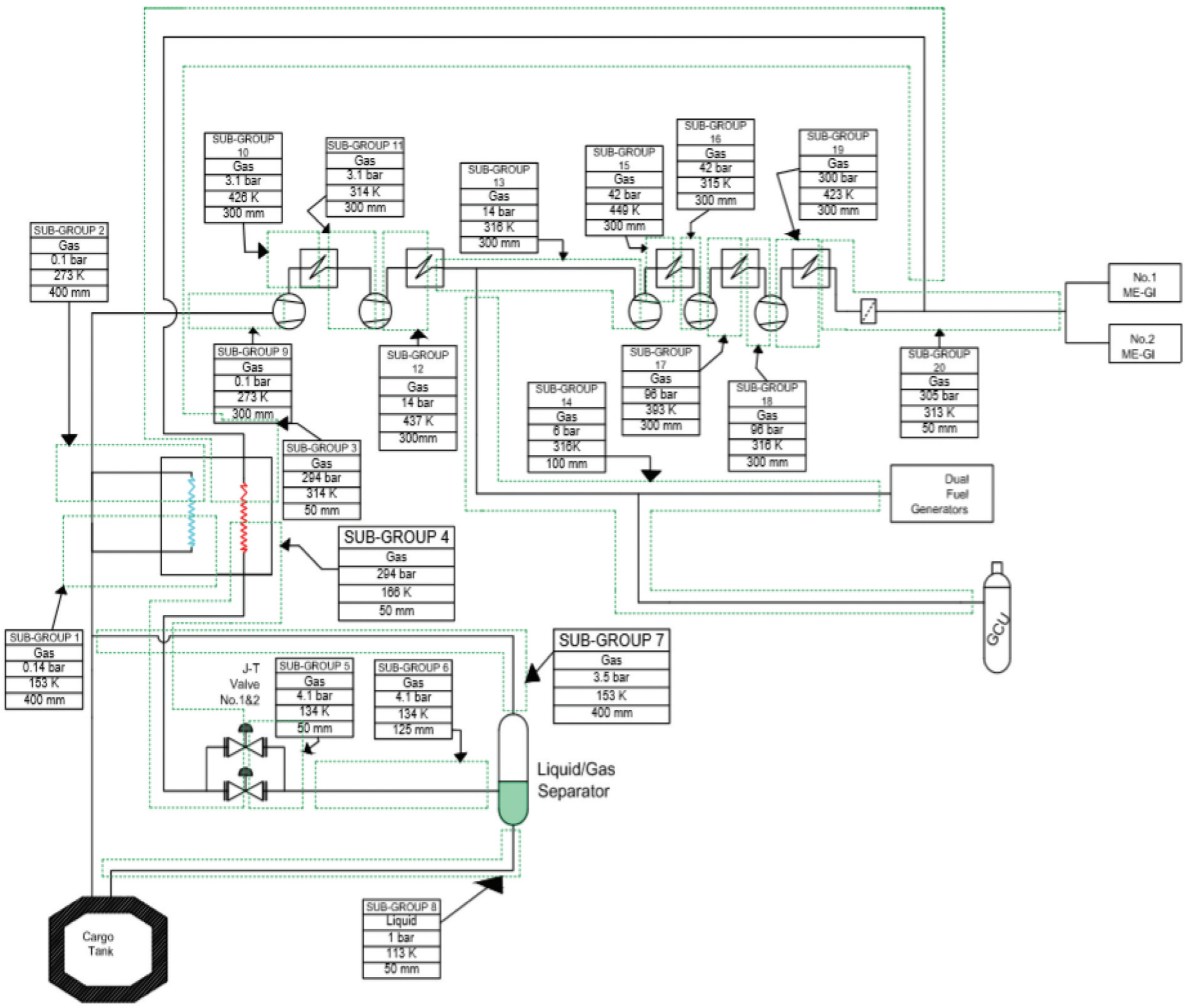

Figure 3. PRS+MRS GA subgroup division.

Accidental scenarios

The scope of this research was focused on the potential risk pertinent to the two LNG re-liquefaction systems caused by the system failure which may lead to gas leak and spread inside the CCR. This room is located on the freeboard deck of the case ship without any structural enhancement against fire or explosion: it is simply because the current regulations do not require such enhancements. Under this circumstance, this research was to evaluate the potential risks that may lead to fire/explosion by estimating gas concentration ratio inside the room in the event of gas leaks, taking into account the capacity of ventilation system. The defined accidental scenarios were fed into the quantitative risk analyses.

Frequency analysis

The frequency analysis is the quantification of the probability of the pre-defined accidental scenarios in Scenario Analysis, using numerical calculations and frequency data. The frequency of initial leak for each subgroup was analysed, whereas three representative leak hole diameters were considered: 50 mm (representing 0–50 mm), 100 mm (representing 50 mm-100 mm), and full rupture size (100 mm-max. component size).

Furthermore, the leak flow rate from these holes was calculated for all the subgroups of the two systems.

In this section, the probability of leakage occurring per year was calculated with the aid of DNV's failure frequency data guidance (DNV, 2012). Furthermore, the leak flow rate of each subgroup depending on the three different hole sizes is calculated. More specifically, by approximating the atmospheric to gauge pressure, the formulae used are:

$$Q_g = \frac{1.4 \times 10^{-4} d^2 \sqrt{\rho_g P_g}}{\rho_g}$$

where,
Q_g: Gas release rate (m^3/s)
d: Hole diameter (mm)
ρ_g: Methane gas density (kg/m^3)
P_g: Pressure of methane gas (bar gauge)
For the liquid leak rate:

$$Q_L = \frac{2.1 \times 10^{-4} d^2 \sqrt{\rho_L P_L}}{\rho_L}$$

where,
Q_L: Liquid release rate (m^3/s)
ρ_L: Methane liquid density (kg/m^3)
P_L: Pressure of methane liquid (bar gauge)

As far as the liquid release rate is concerned, its volume expands to 600 times. Such a gas expansion is input into the resulting analysis as gas leakage rate; No. 8 subgroup is only subjected to this phase transition as the outlet of the separator is in the liquid phase.

Table 2 shows the list and the number of components that each subgroup of P(F)RS contains. In addition, Table 3 represents the leak rate as well as the estimated frequencies for leak hole sizes at the representative diameters of 50 mm, 100 mm, and full rupture.

On the other hand, Table 4 reveals the list of components for the PRS+MRS. This re-liquefaction system has two extra subgroups in addition to the P(F)RS. Table 5 shows the gas and liquid leak rates with their frequency.

Consequence analysis

Considering the estimated leak rates, the gas dispersion simulations were conducted with the help of PyroSim which is a CFD tool specialised in fire and gas dispersion analyses, using Fire Dynamics Simulation code as designed by Thunderhead

Table 2. Equipment list for P(F)RS.

	Subgroup																			
Equipment List	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Actuated Valves	2	2	2	0	2	1	1	1	1	0	0	0	1	2	0	0	0	0	0	1
Manual Valves	0	0	1	0	0	0	0	0	1	0	0	0	1	3	0	0	0	0	0	2
Flanges	4	4	6	0	4	2	2	2	4	0	0	0	4	10	0	0	0	0	0	6
Heat Exchanger	0	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	1	0
Pipe (m)	2	3	6	4	3	1	2	3	2	2	2	2	1	7	2	2	2	2	2	5
Compressor	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	1	0
Separator	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Small Gauge Fittings	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Filter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 3. P(F)RS Initial Leak Frequency.

	Leak Rate (m^3/s)			Frequency of Leak (/year)		
Subgroup	50 mm	100 mm	Full Leak	50 mm Leak	100 mm Leak	Full Leak
1	0.31	1.24	19.89	2.18E-04	2.44E-05	7.74E-05
2	0.17	0.67	10.65	2.22E-04	2.51E-05	8.08E-05
3	0.45	-	-	1.93E-03	-	-
4	0.31	-	-	1.06E-04	-	-
5	0.28	-	-	1.58E-04	-	-
6	0.28	1.12	1.75	3.49E-04	1.59E-04	1.79E-04
7	0.30	1.21	19.42	1.41E-04	1.29E-05	5.23E-05
8	16.47	-	-	1.54E-04	-	-
9	0.42	1.67	14.99	1.77E-04	2.02E-05	6.79E-05
10	0.52	2.08	18.71	6.86E-03	1.44E-03	1.00E-03
11	0.45	1.78	16.04	6.49E-05	1.48E-06	2.72E-05
12	0.53	2.10	18.93	6.86E-03	1.44E-03	1.00E-03
13	0.44	1.78	15.98	1.73E-04	1.94E-05	6.45E-05
14	0.45	1.78	-	2.97E-04	1.74E-04	-
15	0.53	2.13	19.16	6.86E-03	1.44E-03	1.00E-03
16	0.43	1.74	15.64	6.49E-05	1.48E-06	2.72E-05
17	0.49	1.96	17.67	6.86E-03	1.44E-03	1.00E-03
18	0.42	1.69	15.19	6.49E-05	1.48E-06	2.72E-05
19	0.54	2.17	19.52	6.86E-03	1.44E-03	1.00E-03
20	0.45	-	-	5.85E-04	-	-

Table 4. Equipment list for PRS+MRS.

	Subgroup																					
Equipment List	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Actuated Valves	2	3	2	0	0	2	1	1	1	1	0	0	0	1	2	0	0	0	0	0	1	2
Manual Valves	0	0	1	0	0	0	0	0	0	1	0	0	0	1	3	0	0	0	0	0	2	7
Flanges	4	6	6	0	0	4	2	2	2	4	0	0	0	4	10	0	0	0	0	0	6	18
Heat Exchanger	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	1	0	1
Pipe	2	3	6	4	3	3	1	2	3	2	2	2	2	1	7	2	2	2	2	2	5	10
Compressor	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	1	0	2
Separator	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Small Gauge Fittings	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3
Filter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Table 5. PRS+MRS Initial Leak Frequency.

	Leak Rate (m^3/s)			Frequency of Leak (/year)		
Subgroup	50 mm	100 mm	Full Leak	50 mm Leak	100 mm Leak	Full Leak
1	0.31	1.24	19.89	2.18E-04	2.44E-05	7.74E-05
2	0.17	0.67	10.65	2.22E-04	2.51E-05	8.08E-05
3	0.45	-	-	1.93E-03	-	-
4	0.31	-	-	1.06E-04	-	-
5	0.30	-	-	5.74E-05	-	-
6	20.75			1.58E-04		
7	20.75	82.99	129.68	3.49E-04	1.59E-04	1.79E-04
8	0.30	1.21	19.42	1.41E-04	1.29E-05	5.23E-05
9	16.47	-	-	1.54E-04	-	-
10	0.42	1.67	14.99	1.77E-04	2.02E-05	6.79E-05
11	0.52	2.08	18.71	6.86E-03	1.44E-03	1.00E-03
12	0.45	1.78	16.04	6.49E-05	1.48E-06	2.72E-05
13	0.53	2.10	18.93	6.86E-03	1.44E-03	1.00E-03
14	0.44	1.78	15.98	1.73E-04	1.94E-05	6.45E-05
15	0.45	1.78	-	2.97E-04	1.74E-04	-
16	0.53	2.13	19.16	6.86E-03	1.44E-03	1.00E-03
17	0.43	1.74	15.64	6.49E-05	1.48E-06	2.72E-05
18	0.49	1.96	17.67	6.86E-03	1.44E-03	1.00E-03
19	0.42	1.69	15.19	6.49E-05	1.48E-06	2.72E-05
20	0.54	2.17	19.52	6.86E-03	1.44E-03	1.00E-03
21	0.45	-	-	5.85E-04	-	-
22	0.08	0.33	2.97	1.51E-02	3.13E-03	3.52E-03

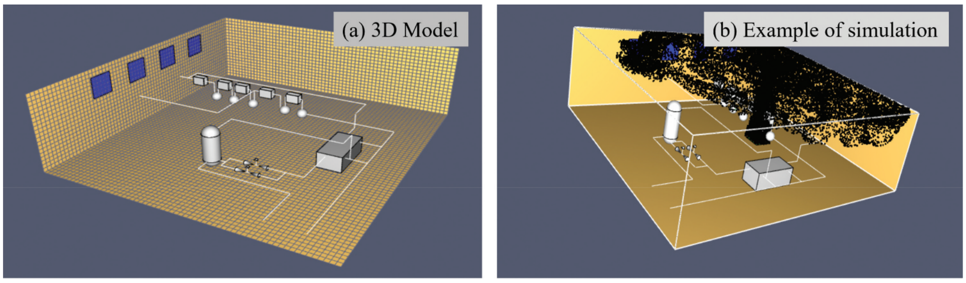

Figure 4. 3D model.

Engineering Ltd. Figure 4(a) shows the simulation models, whereas Figure 4(b) presents an example of simulation.

Both cases have the same room dimension (25 m × 27 m × 8 m), concerning the arrangement of cargo compressor room for the case ship. The gas or liquid leakage of each subgroup is simulated with the corresponding leak rate of each leak hole (50 mm, 100 mm, and Full leakage), calculated from the frequency analysis. In addition, the analogous location of each leakage in the plants is taken into consideration.

By reflecting the original vessel arrangement, four sets of the ventilation were placed at the bow side of the ship and the length of each vent is 1,897 mm with a square shape. Furthermore, a set of gas detector was placed in the middle of the room to measure methane's volume fraction with respect to the air in the room.

Given the fact that the purpose of this research is to keep the room safe against the high gas concentration in the room, which may lead to fire or explosion with a source of ignition; therefore, in case that the gas concentration rate is 5% and above, the accidental scenarios are regarded as "not safe." Considering that the gas concentration is highly affected by the performance of the ventilation systems, parametric studies pertaining to the capacity and the arrangement of ventilation systems are conducted. This gas dispersion for each scenario was simulated with PyroSim software.

After the mesh conversion test, the number of cells was determined to be 88,320 and the simulation method of VLES (Very Large Eddy Simulation) was chosen to analyze larger turbulent fluctuations than LES (Large Eddy Simulation (Labois & Lakehal, 2011)).

The LNG mostly consists of methane so that the gas in the simulation was assumed to be 100% pure methane; the LNG composition varies from region to region, thereby a simple configuration was adopted.

Risk assessment

The risk can be defined as the product of the likelihood of an accident's occurrence and its consequence. For this research, the risk is defined as a condition where the gas concentration in the CCR is above an acceptable level (5% and higher in air). Therefore, the combination of the results from the frequency and consequence analysis can determine the risk level of the two different complex re-liquefaction systems.

The cumulative frequencies corresponding to the dangerous subgroups identified in the simulation (resulting in a gas concentration level 5% or high in air) are integrated and finally represent the overall risk of these systems.

Results of risk assessment

Risk assessment was carried out in order to investigate the sensitivity of two different parameters on the risk levels: the capacity and the arrangement of ventilation systems in the concerned room.

Case 1: ventilation capacity

The minimum requirement of the ventilation capacity is 30 times volume change inside the CCR/hour in accordance with the IMO MSC Circular 72/16 (Skjong, 2002). In addition to this, two additional scenarios with 60 times and 120 times were compared to the base scenario. The study results show the effect of ventilation capacity on the gas concentration in the room, presenting the overall risk level of the LNG re-liquefaction system.

Tables 6 and 7 show the results of the analysis for P(F)RS and PRS+MRS, respectively. This result is generated by simulating all ventilation capacity cases and adding all frequencies corresponding to subgroups with a methane/air volume ratio (mol/mol). It has been found that for 30 ventilation changes, the PRS+MRS system (9.592E-03 times per year) has a relatively higher risk than P(F)RS (5.595E-03 times per year). On the other hand, an interesting phenomenon has been discovered that as the ventilation capacity increases, the risk gap between the two systems is narrowed. In other words, the effectiveness of the ventilation system can be found in both systems, but you can see that PRS+MRS is more effective for ventilation.

It has been found that the risks increase as the application of the system becomes more complex. Therefore, it is necessary to consider appropriate responses to these trends.

In addition, this finding can help enhance our understanding of the relation between ventilation capacity and system complexity. Hence, these results can be good information for future regulatory frameworks.

Case 2: ventilation capacity 120 times/hour with optimal vent allocation

Case 2 was inspired to determine the effectiveness of the optimal arrangement of ventilation systems on reducing the risk levels of the proposed systems. With a great trial and error, the following ventilation systems were proposed to be arranged: eight sets of ventilation systems with a total ventilation capacity of 120 times/hour as shown in Figure 5. The results can be summarised as with Table 8.

According to the results of Case 2, both systems have lower risk levels at similar levels. From these results, it can be safely estimated that the number of ventilation increases, and the optimal placement will necessarily contribute to lowering the level of risk. Nevertheless, if the risks of two different systems converge to 120 m^3/h, the level of reduction remains the same.

Table 6. Case 1 results for P(F)RS.

	30 times changes					60 times changes			120 times changes			
Subgroup	50 mm	100 mm	Full leak	Safe/Not-safe	LEL-UEL	Full leak	Safe/Not-safe	LEL-UEL	50 mm	Full leak	Safe/Not-safe	LEL-UEL
1	0.64%	1.98%	14.00%	Not-safe	14%	12.40%	Not-safe	12.40%	-	10.60%	Not-safe	10.60%
2	0.41%	1.41%	13.30%	Not-safe	13.30%	10.50%	Not-safe	10.50%	-	7.03%	Not-safe	7.03%
3	0.85%	-	-	Safe	-	-	-	-	-	-	-	-
4	0.66%	-	-	Safe	-	-	-	-	-	-	-	-
5	0.57%	-	-	Safe	-	-	-	-	-	-	-	-
6	0.37%	1.60%	2.22%	Safe	-	-	-	-	-	-	-	-
7	0.40%	1.91%	14.60%	Not-safe	14.60%	12.90%	Not-safe	12.90%	-	11.50%	Not-safe	11.50%
8	13.60%	-	-	Not-safe	13.60%	-	Not-safe	13.00%	9.41%	-	Not-safe	9.41%
9	0.58%	2.32%	11.30%	Not-safe	11.30%	9.29%	Not-safe	9.29%	-	7.05%	Not-safe	7.05%
10	0.59%	2.27%	14.40%	Not-safe	14.40%	12.10%	Not-safe	12.10%	-	10.70%	Not-safe	10.70%
11	0.57%	1.82%	12.20%	Not-safe	12.20%	10.70%	Not-safe	10.70%	-	8.87%	Not-safe	8.87%
12	0.46%	2.63%	14.80%	Not-safe	14.80%	12.10%	Not-safe	12.10%	-	10.00%	Not-safe	10.00%
13	0.41%	2.54%	12.70%	Not-safe	12.70%	10.50%	Not-safe	10.50%	-	7.65%	Not-safe	7.65%
14	0.49%	2.18%	-	Safe	-	-	-	-	-	-	-	-
15	0.57%	2.65%	14.60%	Not-safe	14.60%	12.00%	Not-safe	12.00%	-	6.03%	Not-safe	6.03%
16	0.43%	2.22%	12.30%	Not-safe	12.30%	10.10%	Not-safe	10.10%	-	4.74%	Safe	4.74%
17	0.36%	2.02%	13.50%	Not-safe	13.50%	10.80%	Not-safe	10.80%	-	4.98%	Safe	4.98%
18	0.32%	1.68%	11.70%	Not-safe	11.70%	9.31%	Not-safe	9.31%	-	3.87%	Safe	3.87%
19	0.24%	2.08%	13.60%	Not-safe	13.60%	8.38%	Not-safe	8.38%	-	2.27%	Safe	2.27%
20	0.03%	-	-	Safe	-	-	-	-	-	-	-	-
Total (cumulative frequency)			5.6E-03 times per year			5.6E-03 times per year				3.5E-03 times per year		

Table 7. Case 1 results for PRS+MRS.

	30 times changes					60 times changes					120 times changes				
Subgroup	50 mm	100 mm	Full leak	Safe/Not-safe	LEL-UEL	Sub -group	50 mm	Full leak	Safe/Not-safe	LEL-UEL	Sub -group	50 mm	Full leak	Safe/Not-safe	LEL-UEL
1	0.64%	1.98%	14.00%	Not-safe	14.00%	1	-	12.40%	Not-safe	12.40%	1	-	10.60%	Not-safe	10.60%
2	0.41%	1.41%	13.30%	Not-safe	13.30%	2	-	10.50%	Not-safe	10.50%	2	-	7.03%	Not-safe	7.03%
3	0.85%	-	-	Safe	-	-	-	-	-	-	-	-	-	-	-
4	0.68%	-	-	Safe	-	-	-	-	-	-	-	-	-	-	-
5	0.30%	-	-	Safe	-	-	-	-	-	-	-	-	-	-	-
6	5.02%	-	-	Not-safe	5.02%	6	0.6%	-	Safe	-	-	-	-	-	-
7	7.03%	52.70%	76.80%	Not-safe	7.03%	7	5.01%	-	Not-safe	5.01%	7	1.83%	-	Safe	-
8	0.48%	1.91%	16.20%	Safe	-	-	-	-	Not-safe	-	-	-	-	-	-
9	13.60%	-	-	Not-safe	13.60%	9	13.00%	-	Not-safe	13.00%	9	9.41%	-	Not-safe	9.41%
10	0.58%	2.32%	11.30%	Not-safe	11.30%	10	-	9.29%	Not-safe	9.29%	10	-	7.05%	Not-safe	7.05%
11	0.59%	2.27%	14.40%	Not-safe	14.40%	11	-	12.10%	Not-safe	12.10%	11	-	10.70%	Not-safe	10.70%
12	0.57%	1.82%	12.20%	Not-safe	12.20%	12	-	10.70%	Not-safe	10.70%	12	-	8.87%	Not-safe	8.87%
13	0.46%	2.63%	14.80%	Not-safe	14.80%	13	-	12.10%	Not-safe	12.10%	13	-	10.00%	Not-safe	10.00%
14	0.41%	2.54%	12.70%	Not-safe	12.70%	14	-	10.50%	Not-safe	10.50%	14	-	7.65%	Not-safe	7.65%
15	0.49%	2.18%	-	Safe									-	-	-
16	0.57%	2.65%	14.60%	Not-safe	14.60%	16	-	12.00%	Not-safe	12.00%	16	-	6.03%	Not-safe	6.03%
17	0.43%	2.22%	12.30%	Not-safe	12.30%	17	-	10.10%	Not-safe	10.10%	17	-	4.74%	Safe	-
18	0.36%	2.02%	13.50%	Not-safe	13.50%	18	-	10.80%	Not-safe	10.80%	18	-	4.98%	Safe	-
19	0.32%	1.68%	11.70%	Not-safe	11.70%	19	-	9.31%	Not-safe	9.31%	19	-	3.87%	Safe	-
20	0.24%	2.08%	13.60%	Not-safe	13.60%	20	-	8.38%	Not-safe	8.38%	20	-	2.27%	Safe	-
21	0.03%	-	-	Safe				-	-	-	-	-	-	-	-
22	0.32%	0.68%	5.07%	Not-safe	5.07%	22	-	2.51%	Safe	-	-	-	-	-	-
Total				9.6E-03 times per year					5.9E-03 times per year		-	-		3.5E-03 times per year	

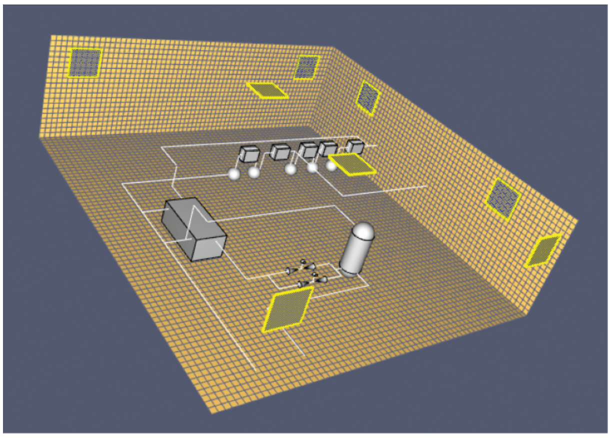

Figure 5. Optimal ventilation allocation.[1]

Comparison and outcome

In this section, a detailed comparison of all the risk assessment results for both systems will be evaluated. Figure 6 shows the quantification of risk, for every ventilation capacity case of the P(F)RS and the PRS +MRS, is plotted in the previous sections. Furthermore, the cumulative frequency results for both re-liquefaction systems are presented in Table 8 with the ventilation capacities sorted in ascending order.

Moving on the IMO's predefined ventilation capacity value of 30 times/hour, it must be highlighted that the PRS+MRS is still an unsafe system, with a big difference in the cumulative frequency value between P(F)RS and PRS+MRS. P(F)RS will cause a dangerous conditions due to leakages at the components, approximately 5.6 E-3/year whereas PRS+MRS at about 9.6 E-3/year. On the other hand, an increase in the ventilation capacity with an optimal arrangement was observed to reduce the risk level as low as 1.0E-3/year. This finding would imply an insight into the future safety framework.

Looking into Figure 7, it is also noticeable that the number of Not-safe subgroups was found to be greater than those of P(F)RS.

For the case of 60 times ventilation, the risk level of P(F)RS remained unchanged; however, the PRS+MRS value decreased sharply to 5.9E-03 times per year. It must be mentioned that once more PRS+MRS is a slightly riskier system in comparison to the other one. According to the following chart, although the number of PRS+MRS "Not-safe" subgroups only decreased from 16/22 to 14/22, the cumulative frequency value has been critically reduced.

As this case's risks lie in unacceptable levels, it was decided that the ventilation capacity will be doubled in order to succeed the reduction of the potential risk.

At 120 times/hour ventilation operation, the risk levels of P(F)RS and PRS+MRS are 3.5E-03 and 3.5E-03 times per year, respectively. Hence, it is obvious that the latter re-liquefaction system in this case is the safer one. Furthermore, concerning the chart below, it is spotted that the number of Not-safe Subgroups and their flammability range percentages are equal for both systems, with only one exemption visible in the third column.

Up to this point, it is observed that, even though the risk level of both systems decreases, their values are at unacceptable levels. Thus, the cumulative frequency results of the 120 times/hour air circulation must be reduced to tolerable risk levels. Moreover, as it is detected that the IMO's regulated ventilation capacity of 30 times/hour quadrupled to 120 times/hour, it was decided that it would be an over exaggeration to increase it above the latter value. For this reason, a more efficient idea would be to change the exhaust vent allocation of the case ship steel arrangement to

Table 8. Case 2 results for P(F)RS vs PRS+MRS.

	P(F)RS				PRS+MRS			
Subgroup	50 mm	Full leak	Safe/Not-safe	LEL-UEL	50 mm	Full leak	Safe/Not-safe	LEL-UEL
1	-	6.95%	Not-safe	6.95%	-	6.95%	Not-safe	6.95%
2	-	4.80%	Safe		-	4.80%	Safe	-
7	-	5.22%	Not-safe	5.22%	-	-	-	-
8	4.98%	-	Safe			-	-	-
9	-	4.89%	Safe		4.98e-02	-	Safe	-
10	-	4.53%	Safe		-	4.89%	Safe	-
11	-	3.86%	Safe		-	4.53%	Safe	-
12	-	6.62%	Not-safe	6.62%	-	3.86%	Safe	-
13	-	5.73%	Not-safe	5.73%	-	6.62%	Not-safe	6.62%
14	-	-	-	-	-	5.73%	Not-safe	5.73%
15	-	3.12%	Safe	-				
16		-	-	-	-	3.12%	Safe	3.12%
Total	1.20E-03 times per year				1.15E-03 times per year			

[1]Vent 1: $X_{min} = 1.5$ m, $X_{max} = 3.7$ m, $Z_{min} = 4.9$ m, $Z_{max} = 7.1$ m, and Y = 27 m (Port-side); Vent 2: $X_{min} = 21.5$ m, $X_{max} = 23.7$ m, $Z_{min} = 4.9$ m, $Z_{max} = 7.1$ m, and Y = 27 m (Port-side); Vent 3: $X_{min} = 1.5$ m, $X_{max} = 3.7$ m, $Z_{min} = 4.9$ m, $Z_{max} = 7.1$ m, and Y = 0 m (Starboard-side); Vent 4: $X_{min} = 21.5$ m, $X_{max} = 23.7$ m, $Z_{min} = 4.9$ m, $Z_{max} = 7.1$ m, and Y = 0 m (Starboard-side); Vent 5: $X_{min} = 19.9$ m, $X_{max} = 22.1$ m, $Z_{min} = 4.9$ m, $Z_{max} = 7.1$ m, and X = 25 m (Bow-side); Vent 6: $Y_{min} = 4.4$ m, $Y_{max} = 6.6$ m, $Z_{min} = 4.9$ m, $Z_{max} = 7.1$ m, and X = 25 m (Bow-side); Vent 7: $X_{min} = 11.4$ m, $X_{max} = 13.6$ m, $Y_{min} = 7.4$ m, $Y_{max} = 9.6$ m, and Z = 8 m (Ceiling); Vent 7: $X_{min} = 11.4$ m, $X_{max} = 13.6$ m, $Y_{min} = 17.4$ m, $Y_{max} = 19.6$ m, and Z = 8 m (Ceiling).

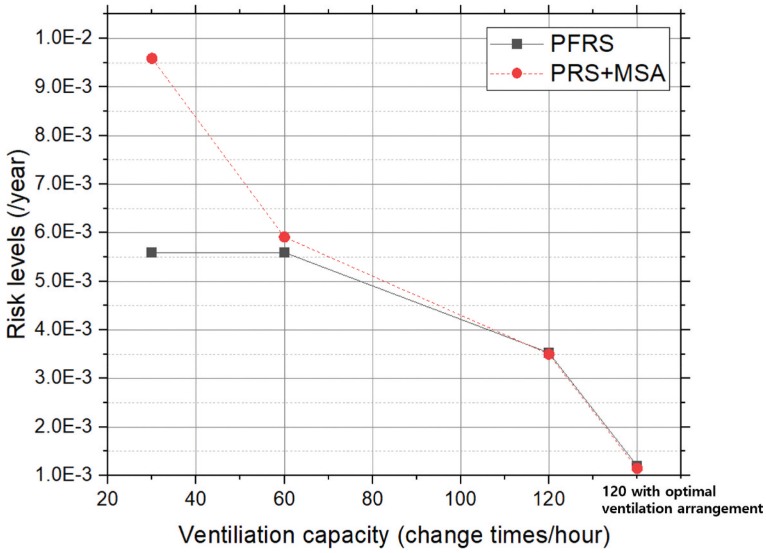

Figure 6. Risk comparison between RFRS and PRS+MRS.

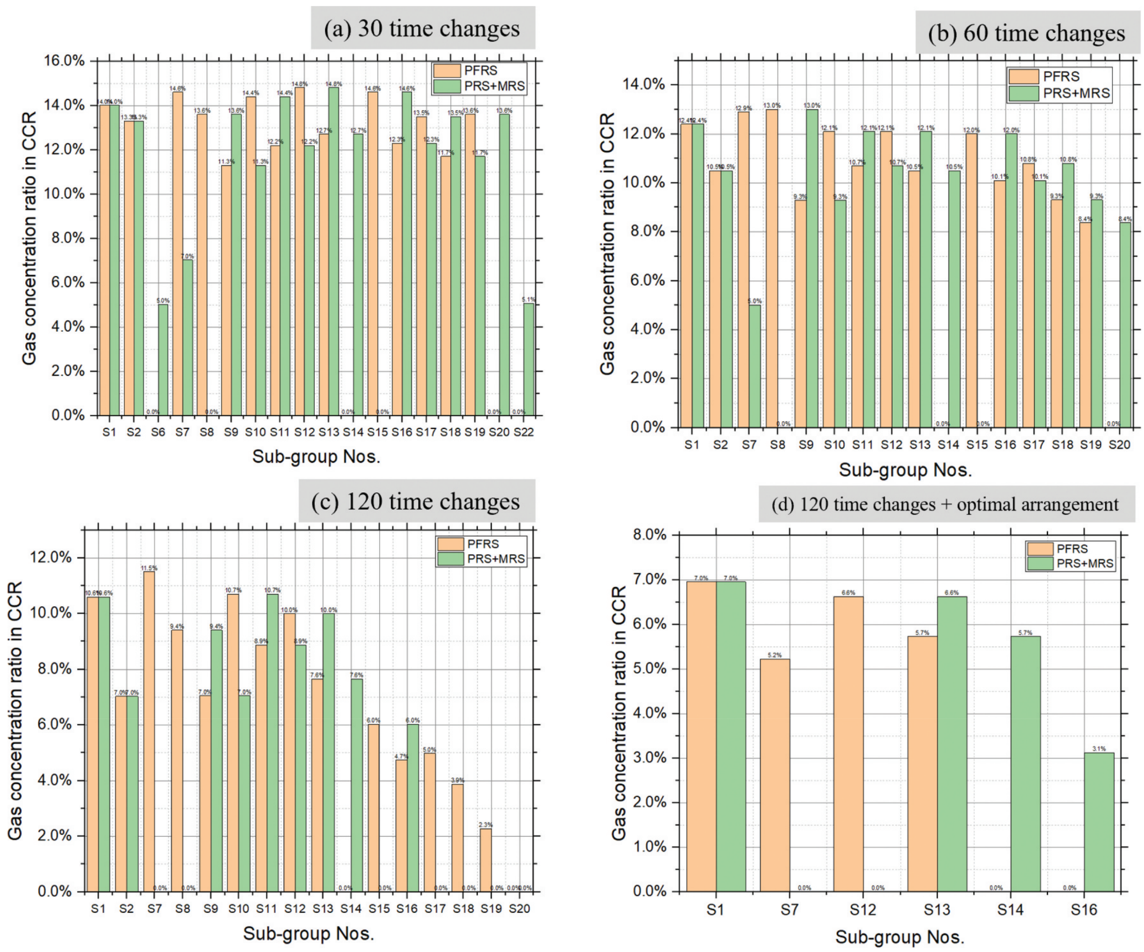

Figure 7. Flammability ranges at various ventilation conditions.

optimal positions inside the CCR. With the new vent distribution, the Not-safe subgroups of the previous case are simulated again. To summarise, the risk level was dropped to 1.198E-03 times per year for P(F)RS and 1.145E-03 times per year for PRS+MRS. In addition, both risk values are situated very close to 1.0E-03, and these differences can be considered negligible. Hence, both re-liquefaction systems can be identified that match the criteria for the maximum tolerable risk of crew members.

Discussion

Given that the proposed LNG re-liquefaction systems are considered credible application for new-built LNG carriers, research findings are expected to contribute to improving the overall safety on board of LNG vessels. The novelty of this research can be placed on the fact that it offers a quantitative insight into the relation between the complex LNG systems and ventilation effects in terms of safety of CCR.

On the other hand, it is observed that even though the IMO's regulated ventilation capacity is increased this much, the cumulative frequency results of both systems approximate the maximum risk acceptance level for the crew and do not appear to be smaller.

In addition, concerning the PRS+MRS, it is mentioned that a methane refrigeration plant was adjusted to the case's ship P(F)RS, in order to conduct the comparative safety assessment. For this plant, the real practice data were insufficient and the pressures, temperatures, pipe diameters, and fuel volume flow rates were approximated by combining knowledge from past academic publications. For this reason, it is reasonable to assume that if data is obtained from a vessel operated by PRS+MRS, it will be closer to actual marine industry practices.

One limitation of this research can be placed on the fact that research findings were not able to propose a safe strategy which could guarantee the As Low As Reasonably Practicable (ALARP) region, which is 1.00E-04 times/year for LNG carriers. Nevertheless, if considering the probability of ignition which leads to final accidental events such as fire or explosion, the risk level of those systems could be further reduced. The quantification of those risks will remain as a next step work.

The effectiveness of the system hierarchical modelling is also worth being mentioned. It was found that the modelling approach was useful to evaluate the individual risk of subcomponents consisting of complex systems.

Meanwhile, it may be argued that it is not realistic to apply 60 (or 120) times air change for safer design because the increase in air change times requires ventilation fans with bigger capacity and results in the increment of capital costs. So, safety always needs to be weighted with the economic impact for the proper decision-making. Given this, a further investigation on the best solution in consideration of both the safety and the economic impacts will be conducted as future works.

Conclusions

The research findings can be summarised as below:

(1) The risk levels were estimated at 5.6 E-3/year for P(F)RS whereas about 9.6 E-3/year for the PRS +MRS in consideration of current regulations (ventilation capacity of 30 times air volume change in the CCR).

(2) It was found that the increase in the ventilation capacity could reduce the risk levels.
- For 60 times change: 5.6E-03 times per year for P(F)RS and 5.9E-03 times per year for PRS +MRS.
- For 120 times change: 3.5E-03 times per year for both P(F)RS and PRS+MRS.

(3) The importance of that the proper arrangement of the ventilation systems was revealed to further reduce the overall risk levels.
- For 120 times change/hour with an optimal arrangement: 1.20E-03 times per year for both P(F)RS and 1.15E-03 for PRS+MRS.
- Considering the fact that the risk reduction of PRS+MRS is greater with increasing ventilation capacity, it has been found interesting that the effect of the ventilation system is more effective for PRS+MRS than P(F)RS.

(4) While new systems are flooding into the marine industry, safety regulations may lag behind this trend. Under this circumstance, research findings are highly believed to offer guidance into future regulatory frameworks as meaningful inputs.

(5) Research findings clearly present that the increment of ventilation capacity will reduce the potential risks against gas leak from LNG re-liquefaction systems in a confined space. Nevertheless, the tolerable levels of those risks need to be further discussed as a future work.

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Disclosure statement

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

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