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CFD implementation to mitigate the LNG leakage consequences: A review of explosion accident calculation on LNG-fueled ships

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Abstract

Liquefied Natural Gas (LNG) has a significant benefit in reducing air pollutants such as sulfur oxide, nitrogen oxide, and particulate matter emitted by Diesel Oil or Heavy Fuel Oil. The International Maritime Organization (IMO) regulates these pollutants in MARPOL Protocol Annex VI. It was implemented by establishing an Emission Control Area (ECA) in 2010 that restricts exhaust gas of ships. This regulation has resulted in new shipbuilding orders or conversions to adopt the LNG-fueled systems. Besides the benefits of LNG fuel, storing, transporting, and distributing this fuel has a different problem with conventional fuels. LNG is volatile, and it has a low flashpoint that could lead to spontaneous ignition. To assess the safety and mitigation for LNG-powered ships, Computational Fluid Dynamics (CFD), such as Kameleon Fire Ex (KFX) and Flame Acceleration Simulator (FLACS), is considered to simulate the LNG release. This technical measure is taken to observe the possible damage or loss due to the cryogenic effect, the extreme temperature of the jet fire, or Vapor Cloud Explosion (VCE). These consequences could happen sequentially that known as the “Domino Effect”. The effect of the leak and environment-related parameters could influence the severity of the damage. The applications of CFD for the LNG release cases are discussed and highlighted in this review.

Keywords: *LNG Leakage; Computational Fluid Dynamics; Gas Dispersion; Jet Fire; Vapor Cloud Explosion*

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1. Introduction

The international shipping industries, including activities in Southern Sea Route and Northern Sea Route (Cao et al., 2016; Prabowo et al., 2016; Prabowo et al., 2018; Yusvika et al., 2020), have contributed to 2.7% of global air pollution or 870 million tons of CO_2 (Buhaug et al., 2009). Other air pollutants such as sulfur dioxide, nitrogen dioxide, and particulate matter have also been a concern in the effort to preserve clean air. As a response, the International Maritime Organization (IMO) has issued Annex VI which is highlighted in the International Convention for the Prevention of Pollution from Ships (MARPOL) (MARPOL, 1998). This regulation has mentioned the restriction of airborne emissions in specific areas as the Emission Control Area (ECA) which includes the Baltic Sea, North Sea, North America ECA, Canadian coast, and the US Caribbean ECA (MARPOL, 1998). ECA is designated to limit no more than 0.10% m/m of sulfur dioxide, and no more than 3.4 g/kWh of nitrogen dioxide (IMO, 2019). As a consequence, numerous alternatives for reducing pollutant emissions have been proposed, including adding a selective catalyst reduction device on the exhaust system, utilizing low-sulfur fuel oil, or substituting conventional fuel with liquefied natural gas (LNG) (Notteboom, 2011; Adachi et al., 2014; Wang and Notteboom, 2014). LNG is a cleaner fuel and still abundant which is a promising alternative fuel for the shipping industry (Kumar et al., 2011). Rather than conventional fuels such as heavy fuel oil and diesel oil, LNG can reduce the air pollutant emission by 33.7% (Yoo, 2017). Table 1 exhibits the comparison of conventional and LNG fuels for marine use by its emission factor.

Table 1. Comparison of emissions factor (LeFevre, 2018)

Pollutants	Fuel types (g/g of fuel)		
	HFO	MDO	LNG
Sulfur dioxide	0.049	0.003	-
Carbon dioxide	3.114	3.206	2.750
Nitrogen dioxide	0.093	0.087	0.008
Particulate matter	0.007	0.001	-

Aside from the environmental benefits, LNG usage should be checked for reliability and safety. If the LNG fuel was accidentally released, it might easily evaporate and disperse, exposing the surrounding area in danger. Asphyxiation, cryogenic burns, structural damage, fire, and vapor cloud explosion (VCE) could all arise as a result of the natural gas cloud (Lee et al., 2015). Obstructions such processing equipment can further escalate the likelihood of VCE. Because combustible gas accumulates in large quantities, the gas cloud may ignite, resulting in a catastrophic explosion (Paik et al., 2010). In the chain event of an accident, consequences such as a gas leak, fire, VCE, and boiling liquid expanding vapor explosion (BLEVE) can occur simultaneously or consecutively, which is known as the "domino effect". A jet fire that heated the pressure liquid vessel to boiling point can cause BLEVE, which is resulting in a catastrophic accident (Gómez-Mares et al., 2008). A single explosion is a common cause of the domino effect, which can result in gas leaks and fires around the source of the explosion (Kadri et al., 2014). Blast, heat, or fragmentation could damage a neighboring system, resulting in equipment failure. Experimenting with explosion research in an LNG processing plant comes at a significant cost. This type of experiment would necessitate a full-scale model and should be carried out well away from inhabited regions. As a solution, the computational fluid dynamics (CFD) method can be used to do explosive analysis or research. The CFD approach has considerably advanced in recent years, and it can now predict a complex VCE (Nubli and Sohn, 2021a). However, the CFD code must be validated first, and a mesh sensitivity analysis should be conducted to ensure the accuracy of the result.

This paper presents the phenomenon related to accidental LNG releases, discusses several procedures for the modeling and analysis of possible consequences caused by LNG releases. In addition, this paper is concerned with the accidental LNG release in the scope of ships and offshore structures.

2. Safety for Gas-Carrying and Gas-Fueled Ships

LNG is an environmentally friendly fuel that may be used whenever and without restriction, and it is simple to produce because it is extensively used (Nubli, 2021). Apart from the benefits of LNG fuel, there is a difficulty with the installation of equipment, storage, bunkering, and transportation of LNG. Because LNG storage needs an insulated separate tank, it may take up more room than typical storage tanks, which may be easily incorporated into the ship hull (Eide, 2010). As compared to conventional ships, LNG-fueled ships require additional space to accommodate the fuel gas supply system (FGSS), which includes gas fuel storage. As indicated in Fig. 1, there are two types of FGSS configurations: open-deck (Fig. 1b) and dependent (Fig. 1a).

a b

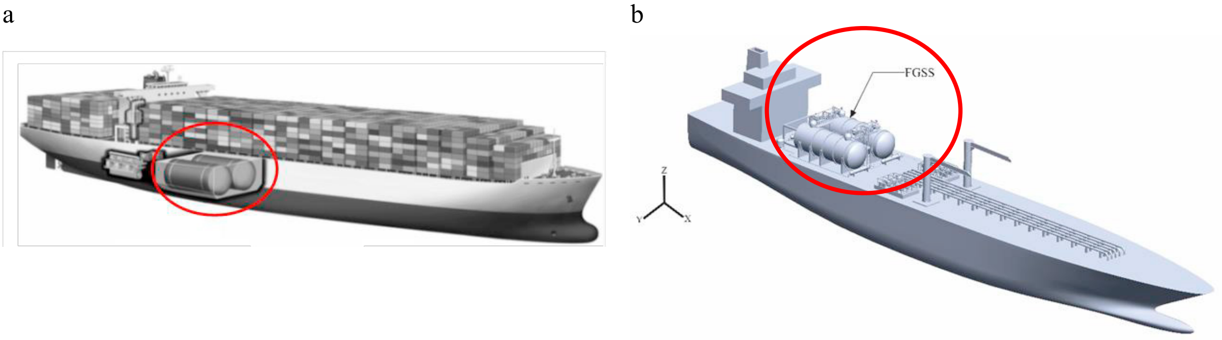

Fig. 1. (a) The dependent FGSS (Adachi et al., 2014), and (b) open-deck FGSS configurations (Nubli, 2021)

The open-deck FGSS arrangement offers several advantages, including simplicity of equipment assembly because the FGSS is positioned on the main deck and there is no need to disassemble the ship hull, natural ventilation if a gas leak occurs, and a reduced risk of FGSS damage if the ship collides or grounding (Nubli et al., 2020a,b; Nubli and Sohn 2021a; Nubli, 2021). In addition, the IGF code suggests that FGSS be installed on the open-deck area for the safety reason (IGF, 2014).

The storage tank, flash tank, high-pressure compressor set, BOG (boil-off gas) compressor set, LNG vaporizer, and BOG condenser set all are part of the FGSS equipment. The FGSS is responsible for storing, vaporizing, and re-liquefying LNG fuel. Before being utilized by the main engine, the LNG fuel from the storage tank must be vaporized. The boil-off gas issue is managed by the BOG system in this system (Park et al., 2018; Nubli and Sohn, 2021a). On the storage tank, the LNG might be naturally evaporated. The heat produced surrounding the storage tank is to cause. As a result, the boil-off gases should be condensed and stored as liquid fuel in the storage tank (MAN B&W, 2014). This method demands the use of a cooling system that uses water or glycol as the coolant. Fig. 2 depicts typical fuel gas processes.

3. Natural Gas Release

Researchers in the field of risk assessment faces a difficult task in modeling an accidental gas release. For safety reasons, the implications of the dangerous gas emission must be known. As a result, gas dispersion tests must be carried out. Few notable large gas release experiments have been conducted previously, which are summarized in Table 2. For the determination of gas release scenarios, a probabilistic approach can be used, with historical event data serving as main data, which includes leakage and environmental parameters. Leak diameter, leak position, leak direction, release rate, and release duration could be employed to define the leakage parameter (Kim, 2016; Nubli and Sohn, 2021a). The environmental parameters such as wind speed, wind direction, atmospheric stability, and ambient temperature are commonly applied (Nubli and Sohn, 2021a). The frequency value has been used to represent all of the historical event data in the parameters. The historical data can be found in the official institutions or companies conducting the statistic analysis. For example, the UK Health and Safety Executive (HSE) and International Association of Oil & Gas Producers (OGP) were issued the failure rates of equipment for the gas processing system (Health and Safety Executive, 2010; OGP, 2010). Moreover, the wind rose chart can also be used that represents the frequency of wind speed and wind direction. In addition, in the current safety industry, a deterministic technique is often utilized to choose the release scenario (Baalisampang et al., 2019; Fu et al., 2016). The variables are fixed as a discrete value in this approach, and the most crucial scenario is usually chosen. On the other hand, a deterministic approach fails to capture the true nature of the physical aspect, which is unstable, uncertain, complex, and ambiguous (Paik, 2019). Table 3 shows past studies with the various approach to generate gas release scenarios.

Table 2. Natural gas release experiments

Test (year)	Mass flow rate (kg/s)	Release duration (s)	Wind speed (m/s)	Source
Maplin Sands (1980)	23.2	160.0	5.5	Dharmavaram et al., 2005
Burro Test (1980)	88.0	167.0	5.6	Koopman et al., 1982
Coyote (1981)	101.0	65.0	6.8	Goldwire et al., 1983
Falcon Test (1987)	202.0	131.0	1.2	Brown et al., 1990
British Gas Spadeadam (1991)	87.9	45.0	6.8	Rian et al., 2016

Table 3. Several past studies using CFD for the gas release modeling

Author (year)	Scenario	Variable(s)
Kim (2016)	Probabilistic	Leak size, leak position, leak direction, wind speed, and wind direction
Seo et al. (2013)	Probabilistic	Wind direction, wind speed, leak rate, release duration, and leak position
Nubli and Sohn (2020b)	Probabilistic	Leak size, leak position, leak direction, wind speed, and wind direction
Baalisampang et al. (2016)	Deterministic	Equipment configuration and leak rate
Fu et al. (2016)	Deterministic	Ambient temperature and mass flow rate

In the probabilistic approach, a histogram can be used to approximate the representation of the data distribution. In this case, the X-axis shows a parameter value, while the Y-axis illustrates the parameter's density value. A fit line, which represents the probability density function, is also included in the histograms. Normal distribution, Weibull distribution, and Linear distribution are among the most often used functions (Nubli, 2021). Furthermore, the probability density functions are deployed to random samplers such as Latin Hypercube and Monte-Carlo samplings, which preserve the distribution of the historical data (Kim, 2016).

The gas release simulation aims to establish the critical zone in the concerned fuel gas supply area. This critical zone helps to control the ignition source, restrict the exposure of non-essential personnel, and to assess local infrastructures for any potential gas accumulation points in case of an incident during bunkering occurred, according to ISO/TS 18683:2015 (EMSA, 2018). In order to measure the critical zone, the flammability limit of the dispersed gas is suggested to apply. For LNG, the limit is ranged from 5% to 15% of LNG concentrations as LFL (lower flammability limit) and UFL (upper flammability limit), respectively (Nubli and Sohn, 2021a). LNG can easily be burned within the flammability limit range. For safety reasons, the LFL can be adjusted to half LFL (2.5% for LNG) (Havens and Spicer, 2005). Fig. 2 exhibits the critical zone measurement by adopting the contour of gas concentrations. In the same case, assessment can be expressed at different points of view (see Fig. 2a; Fig. 2b; and Fig. 2c).

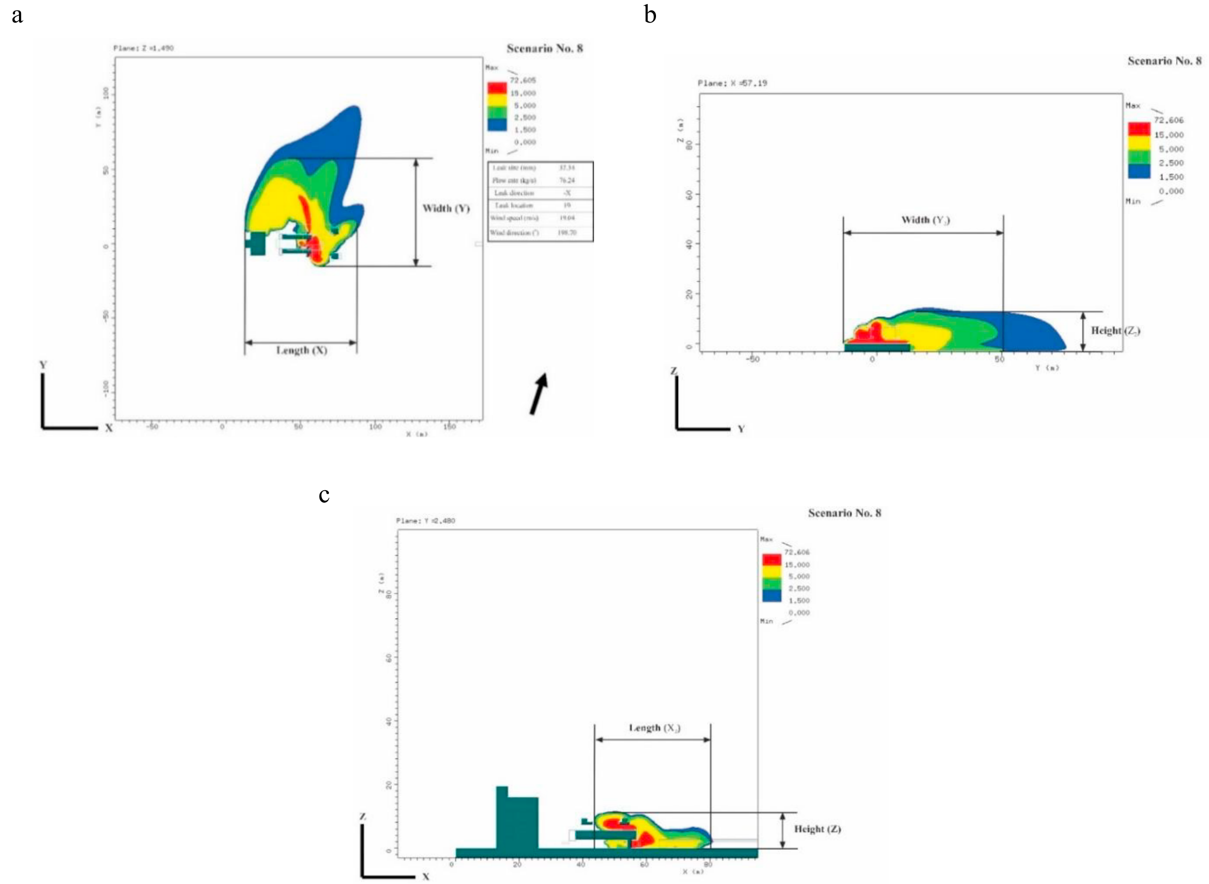

Fig. 2. The contour of gas concentrations in several cross-sections (Nubli, 2021)

4. Vapor Cloud Explosion

In order to create the VCE scenario, both deterministic and probabilistic approaches with different parameters could be adopted. Here, several past studies had been conducted the VCE simulation with various parameters that is shown in Table 4. Nowadays, the CFD code can simulate various mixtures of flammable gas on the VCE simulation, such as hydrogen or hydrocarbon mixtures (Nubli and Sohn, 2021b). CFD codes such as FLACS and KFX can provide various results including blast overpressures, air temperatures, drag forces, etc. Regarding to the blast overpressure, the obstruction and congestion on the object can affect the overpressure magnitude. This finding were proven by performing the sensitivity analysis that deploys various amount of stacked pipe (Bae et al., 2018). A porosity ratio can be used to estimate the void volume of the stacked pipe. The low the porosity is, the low the void volume of the stacked pipe, and it leads to the increase of the blast overpressure (Bae et al., 2018). The blast overpressure can be provided as a contour, for example the KFX result is shown in Fig. 3a. The typical blast overpressure profile is exhibited in Fig. 3b that shows the peak overpressure to the rebound overpressure which has a negative value. The gas filled the void space in the center of the explosion, causing the rebound overpressure.

The peak of blast overpressure can be utilized to establish the design accidental load. The gas explosion frequency and ignition probability of each scenario is used to compose frequency of exceedance due to VCE accident (Nubli and Sohn, 2021b). To appraise the acceptability of the design accidental load, the RAC (risk acceptance criterion) is used such as RAC of UK HSE nad NFPA 59A. This RAC limits the exceedance frequency and categorizes it as the unacceptable, acceptable, and neglibible regions. Fig. 4 exhibits the example of exceedance frequency for VCE that shows the design accidental load as a peak overpressure value.

Table 4. Several past studies on the VCE analysis

Author (year)	Scenario	Variable(s)
Kim (2016)	Probabilistic	Gas cloud volume, center of ignition
Bae et al. (2018)	Deterministic	Number of pipe on the rack, gas cloud located on the rack
Baalisampang et al. (2019)	Deterministic	Leak position, leak direction, and ignition time
Lee (2020)	Probabilistic	Leak size and ignition probability
Kang et al. (2017)	Deterministic	Ignition position, ignition energy, and pipe number on the rack

a b

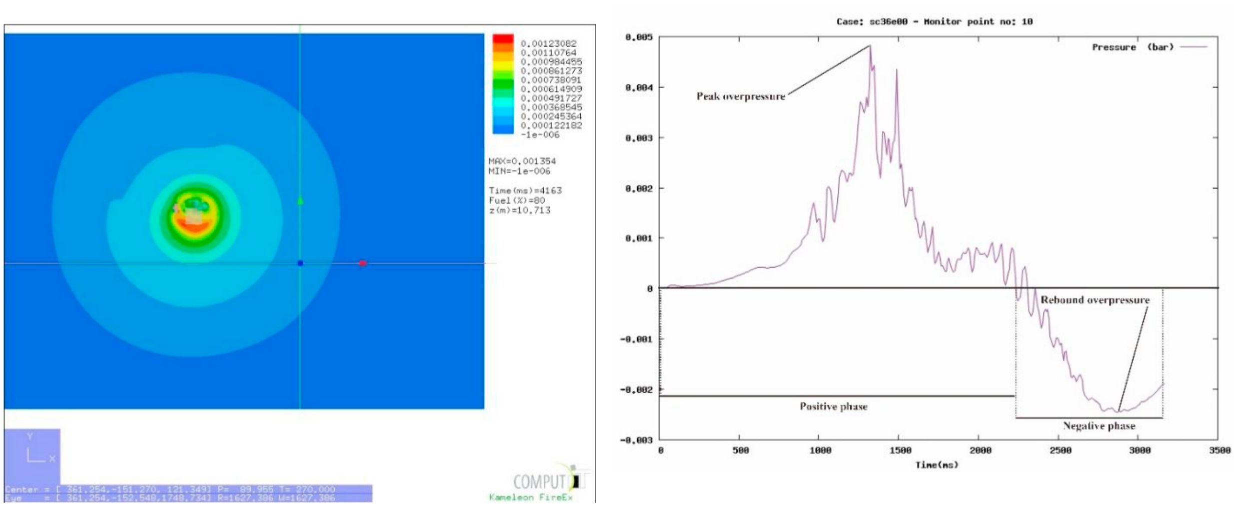

Fig. 3. The blast overpressure by KFX: (a) contour and (b) profile (Nubli and Sohn, 2021b)

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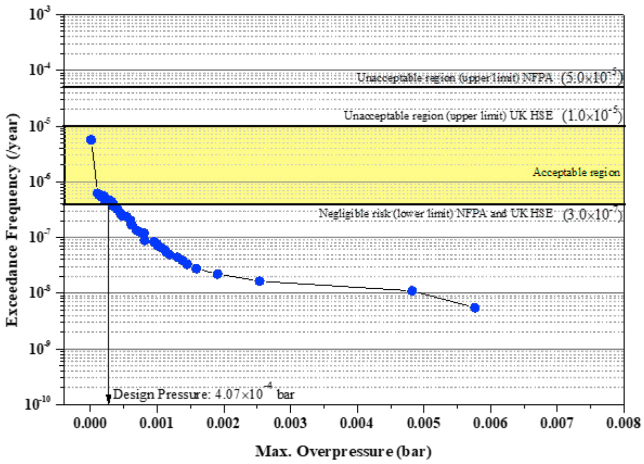

Fig. 4. The design accidental load in the frequency of exceedance (Nubli and Sohn, 2021b)

5. Conclusions

This paper has been presented the application of CFD technology for accident by flammable gas such as gas releases and VCEs. In addition, the problems on the cleaner fuel of marine uses has also been discussed. Here, several points can be concluded as follows,

1. Both gas release and VCE analyses can adopt the deterministic and probabilistic approaches to determine the scenario. For the probabilistic approach, the historical data in frequency can be used. The random sampling methods such as the Latin Hypercube and Monte-Carlo samplings to preserve the distribution of the data.
2. The critical zone can be applied as a result of the gas release simulation. The distance of the gas cloud in the flammability limit is used to determine this zone. The critical zone is designed to control the personnel that enters this region and its activities.
3. The obstruction and congestion in the object of the VCE simulation can affect the magnitude of the blast overpressure. Thus, the VCE simulation is useful to determine the position of equipment or another object in the design of the gas processing layout. In the probabilistic based scenario, the exceedance frequency can be generated by utilizing the gas explosion frequency, ignition probability and its peak overpressure in each scenario.

Overall, the implementation of CFD codes in the gas release and VCE simulations is useful since it is cheaper and saves a lot of time. Various parameters are also can be involved in the simulation that helps to find an adequate result.

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