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CFD Based Simulation of LNG Release during Bunkering and Cargo Loading/Unloading Simultaneous Operations of a Containership

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Abstract: In order to reduce waiting time in port for large LNG (liquefied natural gas) fueled ships, it is suggested that LNG STS (ship to ship) bunkering and cargo loading/unloading should be carried out simultaneously. This study investigated the safety zone of an LNG bunkering vessel with 10,000 cubic meters capacity transferring LNG fuel to an LNG fueled 18,000 TEU containership. Four LNG leakage scenarios were identified based on failure frequencies analysis of piping systems and severity of consequence, three-dimension CFD software FLACS was adopted to calculate flammable cloud dispersion after LNG leakage. As a result, we obtained a rectangle dangerous zone (41.3 m × 126 m), outside of this dangerous zone can be defined as safety zone. It is concluded that safety zone of LNG STS bunkering and cargo loading/unloading SIMOPS (simultaneous operations) cannot keep the same, there are different results for different designs and operation locations. Due to high frequencies and severe consequences, two typical scenarios, the leakage of LNG hose and the natural gas releases from bunkering tank's safety relief valve during bunkering, cannot be ignored in similar study.

Key words: LNG fueled vessel, bunkering, simultaneous operations, gas dispersion, dangerous zone.

1. Introduction

LNG (liquefied natural gas) as marine fuel is a leading alternative for meeting current and future more stringent air emission requirements. To date, there are more than 100 seagoing LNG fueled vessels operating mainly in the North Sea and Baltic Sea, and in China, there are more than 600 inland LNG fueled vessels that are under building or on order [1].

The use of LNG requires the development of bunkering infrastructures and a complete regulatory framework. The feasible bunkering modes are as follows [2]: (1) Truck to ship, (2) Onshore station to ship, (3) Pontoon to ship, (4) Potable fuel tanks, (5) Ship to ship, (6) Offshore unit to ship. In terms of the regulatory framework, in China, Chinese government issued a regulation for LNG bunkering pontoons in 2014, the regulation for LNG bunkering vessels and design code for onshore LNG bunkering stations are under developing, and will be issued in 2016, the complete regulatory systems will promote the formation of waterborne LNG supply chains.

However, due to the complexity of LNG bunkering, in some cases there is a need to provide personalized solutions, such as relative motion limit between two ships, fender arrangement, allowed weather conditions, safety operations zone, etc.

For large ships with large amount LNG fuel, it is suggested that SIMOPS (simultaneous operations) of LNG STS (ship to ship) bunkering and cargo loading/unloading should be carried out to reduce waiting time in port. If loading/unloading operations were in the flammable cloud zone, there would be a risk of fire. In this study, the SIMOPS safety zone of a LNG bunkering vessel with 10,000 cubic meters capacity transferring LNG fuel to an LNG fueled 18,000 TEU containership was addressed.

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2. The Accidents of LNG Bunkering in the History and Enlightenment

The accidents in the history are warning significances in LNG bunkering practice. There is a short history of only 15 years after LNG bunkering appeared in marine sector, only two accidents in Norway have been reported [3].

In Risavika Harbour, during bunkering of MS Bergensfjord on 9 May 2014, there was a leak in the quick release coupling located in the bunkering station on board the ship. The investigation concluded that approximately 130 kg of LNG was released. The incident did not result in personal injuries or damage to property.

The other accident was occurred in Moskenes, during bunkering of MF Landegode on 13 June 2014, the ship's stern moved away from the quay. The hose was stretched, and a davit arm was damaged. The ferry managed to return to the quay, and there was no leak. The bunkering operation continued. The davit arm broke later that day. The incident did not result in any other damages on property, and no persons were injured.

The above two accidents have a certain sense of enlightenment for the safety of LNG bunkering, in details as follows: a safety zone during bunkering should be established, LNG drip trays should be installed, hoses should not be restricted, bunkering station should be continuously monitored, ESD (Emergency Shut Down System) should be tested before every bunkering operation, the breakaway couplings should be installed, mooring procedure should be focused on, enhancing crew training, etc. These safety measures have been considered in the project in this study.

3. The LNG Fueled Ship and the Bunkering Vessel

The LNG fueled ship is an 18,000 TEU containership (Fig. 1 and Table 1) under conceptual design.

A 10,000 cubic meters LNG bunkering vessel (Table 2) with a new type bunkering arm (combination

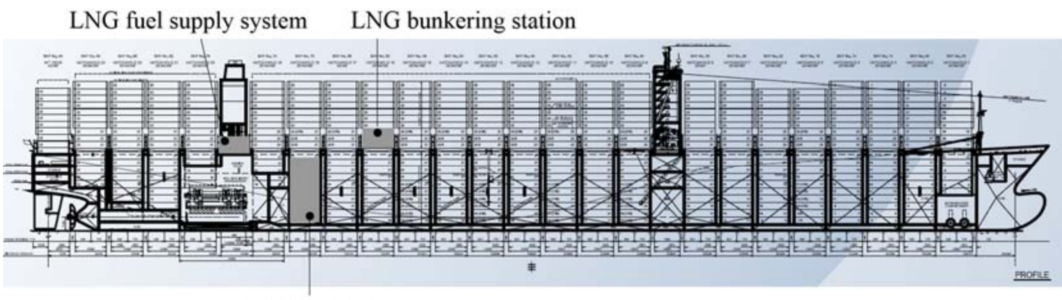


Fig. 1 Basic arrangement of the LNG fueled containership.

Table 1 Basic parameters of the LNG fueled containership.

Length, overall	abt. 403.40 m	Depth, moulded	30.20 m
Length between perpendiculars	abt. 384.00 m	Designed draft, moulded	14.00 m
Breadth, moulded	58.50 m	LNG storage tank	10,000 m^3
Service speed	20 KN	Main engine power	56,800 kW

Table 2 Basic parameters of the LNG bunkering vessel.

Length, overall	abt. 113.50 m	Depth, moulded	5.80 m
Length between perpendiculars	abt. 106.00 m	Designed draft, moulded	12.00 m
Breadth, moulded	20.30 m	LNG storage capacity	10,000 m^3
Max bunkering rate	600 m^3/h	Type of LNG tank	Membrane

of davit, pipes and hoses) was assumed to provide bunkering service for the containership in this study.

4. LNG Leakage Scenarios Definition Based on Failure Frequencies Analysis

In terms of LNG leakage during STS operations, the main focus is LNG bunkering system related receiving ship and bunkering vessel, besides the bunkering system itself, the valves for isolating other systems are involved as well. Due to the safety zone assessment which is the goal in this study, LNG release sources located on open area were only considered. Based on experience and historically data, the flammable gas dispersion after gaseous phase leakage will not influence the safety zone significantly, therefore, liquid phase leakage is the only situation to be considered.

In the field of LNG risk assessment, to define LNG leakage positions and hole sizes based on failure frequencies analysis is becoming an international consensus. As an example, in 2013, the U.S. FERC (Federal Energy Regulatory Commission) issued guidance for the selection of leak sizes based upon failure frequencies for piping systems, in particular, scenarios with failure frequencies greater than 3E-05 per year must be considered [4]. This criterion is used to define hazard scenarios in this study. Currently, there are some databases of failure frequencies available for piping systems, such as FERC [4], OGP [5], TNO [6], HSE [7], etc. Failure frequencies data that are suitable for this project are shown in Tables 3, 5 and 6. Table 4 shows the modified failure frequency and operation times of LNG hose.

Table 7 shows the failure frequencies calculation of bunkering piping systems which are located on open area. Due to lack of failure date of DN 200 valve, the data of DN 150 valve were used conservatively. It can be seen that the failure frequency of LNG hose is the highest (see Table 7).

Hazard scenarios 1-3 identified are listed in Table 8 according to the criteria (failure frequencies greater than 3E-05 per year must be considered). In addition, because of two ships (LNG receiving ship and bunkering ship) are connected together as one during

Table 3 Nominal FERC failure frequencies per unit length for piping.

Pipe diameter	Failure frequency (/yr/m)		
	Catastrophic Rupture	D_{hole} = 1/3d_{pipe}	D_{hole} = 25 mm
d_{pipe} < 50 mm	10E-07	-	50E-07
50 mm < d_{pipe} < 149 mm	5E-07	-	20E-07
150 mm < d_{pipe} < 299 mm	2E-07	4E-07	7E-07

Table 4 Failure frequencies and operation times of LNG hose.

Failure frequency (/hour)	4.0E-7（hole diameter: 10% D~50 mm） D: hose diameter (Refer to Ref. [8]: Modified failure frequency according to TNO purple book)
Operation time every bunkering	16 hours (estimated)
Bunkering times every year	20 times
Total operation time every year	320 hours

Table 5 OGP manual valve failure frequencies (per valve year).

		DN 50	DN 150	DN 300
Hole diameter (mm)	1~3	2.0E-05	3.1E-05	4.3E-05
	3~10	7.7E-06	1.2E-05	1.7E-05
	10~50	4.9E-06	4.7E-06	6.5E-06
	50~150	--	2.4E-06	1.2E-06
	> 150	--	--	1.7E-06

Table 6 OGP actuated valve failure frequencies (per valve year).

		DN 50	DN 150	DN 300
Hole diameter (mm)	1~3	2.4E-04	2.2E-04	2.1E-04
	3~10	7.3E-05	6.6E-05	6.3E-05
	10~50	3.0E-05	1.9E-05	1.8E-05
	50~150	--	8.6E-06	2.4E-06
	> 150	--	--	6.0E-06

Table 7 Failure frequencies of bunkering piping systems on open area.

No.	Type	Length or amount	Specification	Failure frequencies
1	Pipe (liquid)	25 m	DN 200	Catastrophic Rupture: 5.0E-06 Hole diameter 67 mm: 1.0E-05 Hole diameter 25 mm: 1.75E-05
2	Pipe in bunkering arm (liquid)	14 m	DN 200	Catastrophic Rupture: 2.8E-06 Hole diameter 67 mm: 5.6E-06 Hole diameter 25 mm: 9.8E-06
3	Hose in bunkering arm (liquid)	20 m	DN 200	Hole diameter 50 mm: 1.28E-04
4	Actuated valve (liquid)	8 sets	DN 200	Hole diameter 1~3 mm: 2.2E-04 Hole diameter 3~10 mm: 6.6E-05 Hole diameter 10~50 mm: 1.9E-05 Hole diameter 50~150 mm: 8.6E-06
5	Manual valve (liquid)	1 set	DN 200	Hole diameter 1~3 mm: 3.1E-05 Hole diameter 3~10 mm: 1.2E-05 Hole diameter 10~50 mm: 4.7E-06 Hole diameter 50~150 mm: 2.4E-06

Table 8 Hazard scenarios of LNG leakage.

Hazard scenarios	Description	Cumulative time of LNG leakage	Cumulative amount of LNG leakage
Scenario 1	Hose in bunkering arm (liquid), hole diameter is 50 mm	90 s	1,082.7 kg
Scenario 2	Actuated valve (liquid) in bunkering station of receiving ship, hole diameter is 10 mm	90 s	91.3 kg
Scenario 3	Actuated valve (liquid) or manual valve (liquid) in bunkering station of receiving ship, hole diameter is 3 mm	90 s	8.2 kg
Scenario 4	LNG release from safety relief valve of bunkering tank	2.5 s (according to reseating pressure of safety valve, see 4.2.3)	15.0 kg

LNG bunkering, if natural gas releases from vent mast of LNG bunkering vessel, flammable gas probably disperses to LNG fueled ship, and then brings risk. Therefore, scenario 4 is identified (see Table 8). According to experience, ESD total time of 90 s is assumed to consider LNG leakage continuously (60 s for detection and initiation, 30 s for isolation).

5. CFD Analysis of LNG Flammable Cloud Dispersion

Three-dimension CFD software FLACS was adopted to simulate flammable cloud dispersion after LNG leakage. The software is one of authoritative gas dispersion tools worldwide. FLACS has received approval from the US PHMSA (Pipeline and Hazardous Materials Safety Administration) for LNG vapor dispersion modeling scenarios according to federal regulations 49 CFR 193.2059 (a).

The environment conditions of STS operations site are shown in Table 9, and these data are the input of CFD analysis.

Table 9 Environment conditions of STS operations site.

No.	Type	Parameter
1	Annual mean wind speed	3.15 m/s
2	Annual mean temperature	16 °C
3	Atmospheric pressure	101,325 Pa
4	Relative humidity	75%
5	Solar radiation intensity	583 w/m^2
6	Atmospheric stability	D

5.1 Establishment of 3D CFD Calculating Model

Fig. 2 shows the top view and the perspective view of calculating model. Due to pipe outlet type of vent mast which influences gas release and dispersion significantly [9], real pipe outlet was established accurately in 3D model (see Fig. 3).

5.2 Calculations and Analysis

Half of the LFL (lower flammability limit) (volume concentration value 2.5%) of natural gas was accepted as the outer most boundary of the flammable zone.

5.2.1 LNG Leakage from Hose in Bunkering Arm

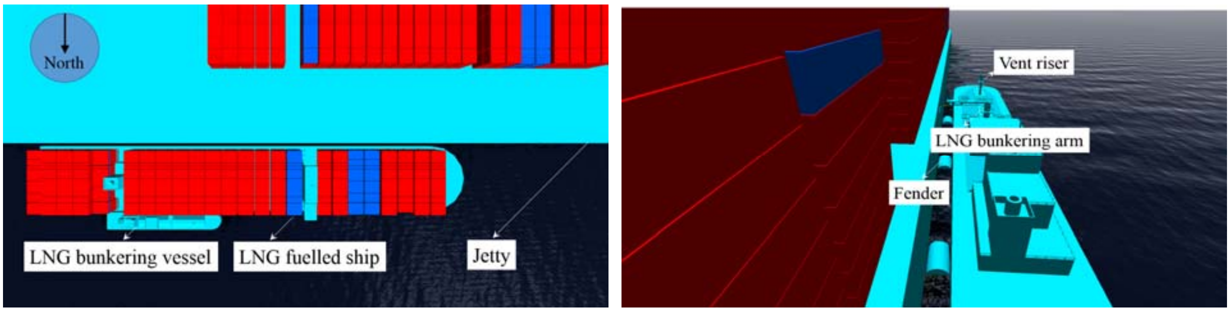
LNG leakage from hose in bunkering arm corresponds to scenario 1 in Table 8. For this scenario, flammable gas would disperse a large range because of a relative large leakage volume, therefore, the dispersion would be sensitive to obstacles surrounding, accordingly, the two situations, unloaded and loaded, are analyzed to compare how the containers (obstacles) influence the gas dispersion. When performing calculations, three wind directions, east, west and north, are considered. (South wind is ignored because of the LNG fueled ship would shelter the gas from wind, the wind directions are shown in Fig. 2.)

(1) Unloaded situation

In this situation, LNG bunkering and containers loading are carried out simultaneously, LNG leakage occurs at the beginning of containers loading. Fig. 4 shows gas dispersion after the LNG was contained by the drip trays (1.2 m × 1.2 m × 0.2 m).

The results calculated show that (Fig. 4), in the north wind situation, flammable gas flowed over the gunwale and spread 27.5 m along the ship transverse direction, in the east and west wind situation, flammable gas was always below the gunwale, therefore, there is no influence on the safety of loading.

When LNG leaks into the water rather than in the bunkering station, there is no harm to the loading operations for flammable gas that was always below the gunwale.



(a) Top view (b) Perspective view

Fig. 2 3D CFD calculating model.

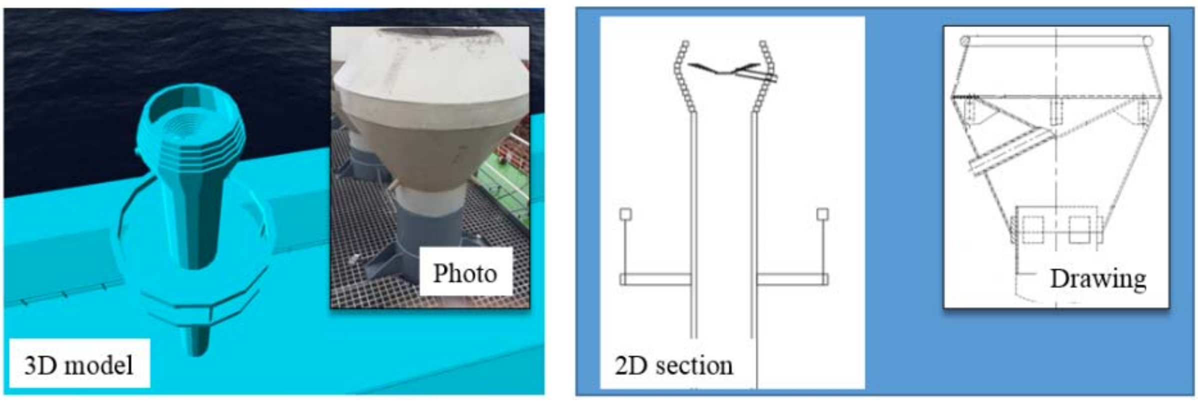
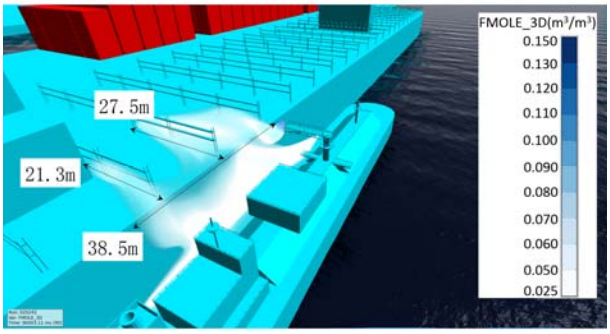
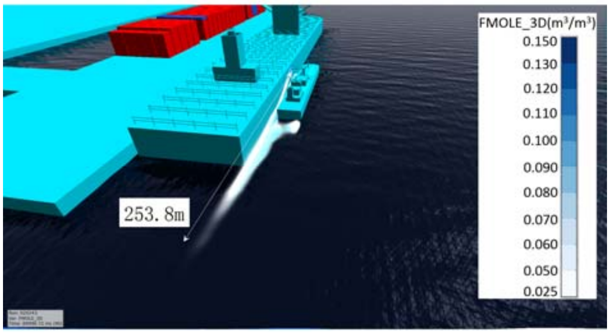


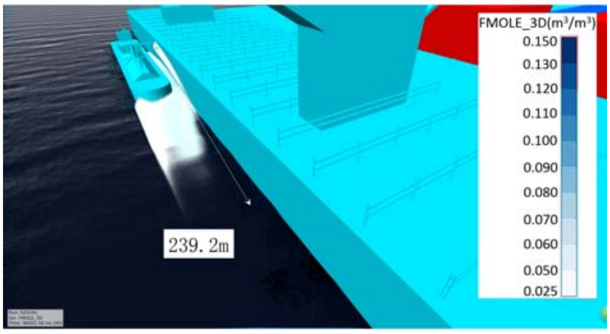
Fig. 3 Pipe outlet model of bunkering vessel's vent mast.



(a) North wind



(b) East wind



(c) West wind

Fig. 4 Flammable gas dispersion range when LNG leakage occurs in bunkering station (volume concentration: 2.5%~15%).

(2) Loaded situation

In this situation, LNG bunkering and containers unloading are carried out simultaneously, LNG leakage occurs at the beginning of containers unloading. Fig. 5 shows gas dispersion after the LNG was contained by the drip trays.

The results calculated show that (Figs. 5, 6), in the north wind situation, flammable gas flowed over the gunwale and spread 14.0 m along the ship transverse direction, in the east and west wind situation, flammable gas was always below the gunwale, therefore, there is no influence on the safety of loading.

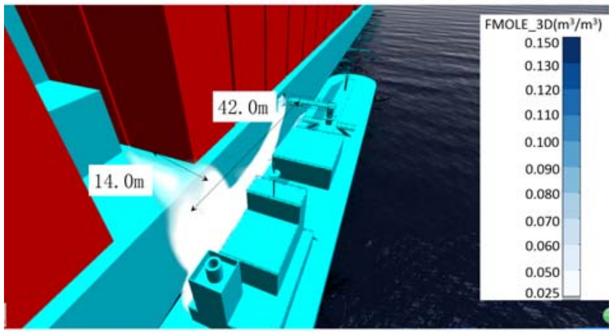
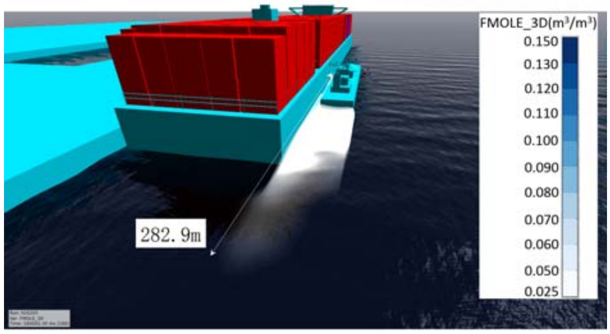
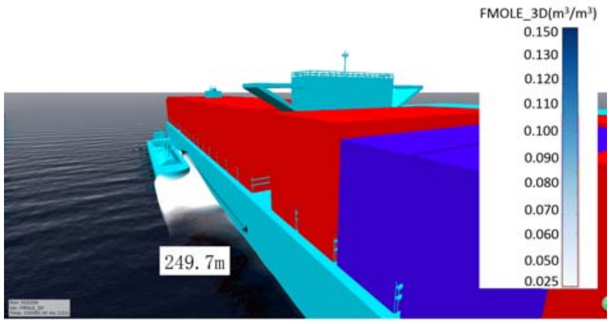


Fig. 5 Flammable gas dispersion range when LNG leakage occurs in bunkering station (north wind, volume concentration: 2.5%~15%).



(a) East wind



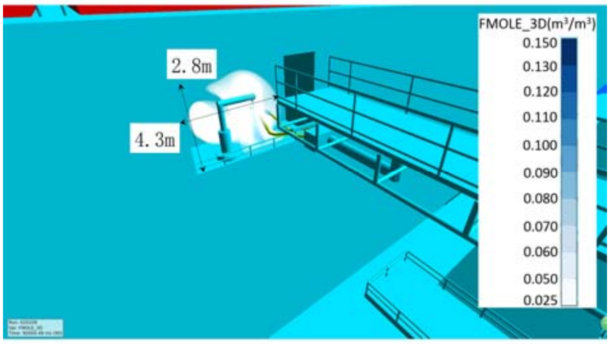
(b) West wind

Fig. 6 Flammable gas dispersion scope when LNG leaks into the water (volume concentration: 2.5%~15%).

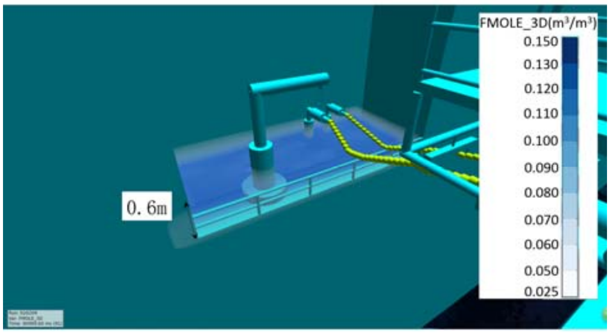
5.2.2 LNG Leakage from Valves

Scenarios 2 and 3 are all regarding LNG leakage from valves in the bunkering station, LNG would be contained by the drip trays.

Calculations are carried out only in north wind situation (In east and west wind situations, the hazards are significantly less by trial calculation). The results (Fig. 7) demonstrate that the range of gas dispersion after valve leakage is very narrow, which does not affect the loading and unloading operations.



(a) Actuated valve leak



(b) Manual valve leak

Fig. 7 Flammable gas dispersion range after LNG leak from valves (north wind, volume concentration: 2.5%~15%).

5.2.3 LNG Release from Safety Relief Valve of Bunkering Tank

LNG bunkering tank's safety valve set and reseat pressures are 0.25 bar and 0.23 bar respectively, and its effective flow area is 31,400 mm^2. In this study, the gas release rate from safety valve was compared by two ways. The result is 6.76 kg/s by gas flow equation [10], and the result obtained from FLACS leak wizard tool is shown in Table 10, the total release time is 2.5 s, the total release mass is 15 kg, therefore, it is reasonable to obtain natural gas release parameters based on FLACS software.

The distance from vent outlet to the farthest boundary of flammable cloud is 10.1 m (Fig. 8), however, the distance from the bunkering vessels vent outlet to the containership's deck edge is 12.7 m during bunkering operations, therefore, ignition hazard due to natural gas release from safety relief valve can be ignored.

5.2.4 Safety Zone

Based on the above calculations, initial rectangle dangerous zone (27.5 m × 84.0 m) is obtained by dangerous distances envelopment, conservatively, the final dangerous zone (Fig. 9) is a new rectangle (41.3 m × 126.0 m) which is obtained from every initial rectangle length that is multiplied by 1.5. Outside the range of the final dangerous zone, it can be defined as safety zone of simultaneous operations.

Table 10 Natural gas release rates from safety valve.

Time (s)	Release rates (kg/s)
0	6.7621
0.5	6.5937
1	6.4242
1.5	6.3364
2	6.0762

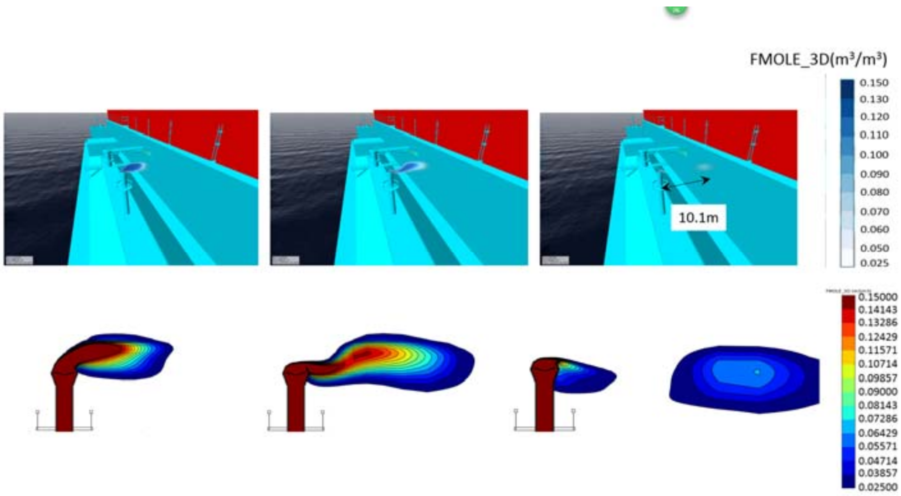


Fig. 8 Flammable gas dispersion range after safety valve takeoff (time: 2 s, 3 s, and 4.56 s).

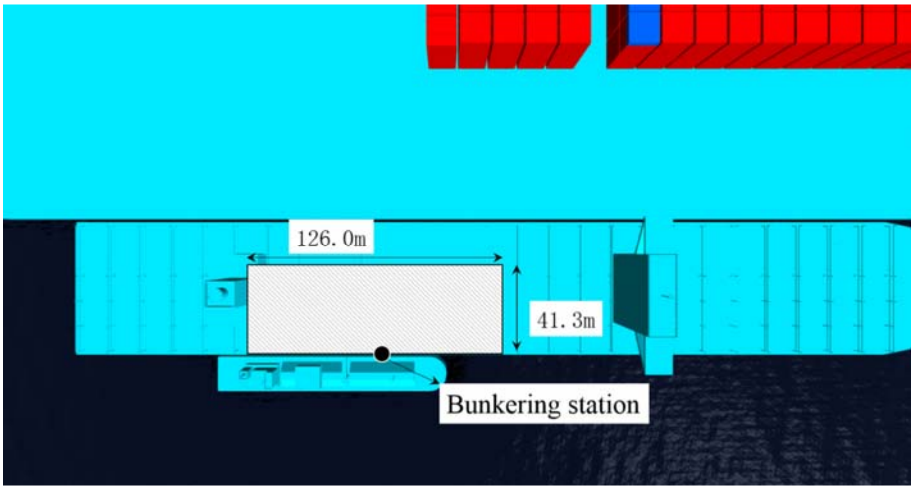


Fig. 9 Dangerous zone.

6. Conclusions

The main conclusions obtained in this study are summarized below:

(1) Due to LNG leakage and gas dispersion which are influenced by ship design and environment conditions significantly, the safety zone of LNG STS bunkering and cargo loading/unloading SIMOPS cannot keep the same, there are different results for different designs and operation sites.

(2) Because the failure frequency of LNG hose is high and flammable gas dispersion range is large after natural gas released from safety relief valve, the scenarios of LNG hose rupture and natural gas released from bunkering tank's safety relief valve cannot be ignored in similar study.

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