Journal of the Korean Society of Marine Environment & Safety
Vol. 19, No. 2, pp. 225-231, April 30, 2013 (pISSN 1229-3431 / eISSN 2287-3341)
Research Paper
http://dx.doi.org/10.7837/kosomes.2013.19.2.225

An Examination on the Dispersion Characteristics of Boil-off Gas in Vent Mast Exit of Membrane Type LNG Carriers

Ho-Keun Kang[*†]
[*] Institute of Ship & Ocean Systems Engineering, Korean Register of Shipping, Seoul, 150-871, Korea

멤브레인형 LNG선박 화물탱크 벤트 마스트 출구에서의 BOG 확산 특성에 관한 연구

강호근[*†]
[*] 한국선급 선박해양시스템연구원

Abstract : *Liquefied gas carriers generally transport cargoes of flammable or toxic nature. Since these cargoes may cause an explosion, fire or human casualty, the accommodation spaces, service spaces and control stations of liquefied gas carriers should be so located as to avoid ingress of gas. For this reason, the paragraph 8.2.9 of IGC Code in IMO requires that the height of vent exits should be not less than B/3 or 6 m whichever is greater, above the weather deck and 6 m above the working area and the fore and aft gangway to prevent any concentration of cargo vapor or gas at such spaces. Besides as known, the LNG market has been growing continually, which has led to LNG carriers becoming larger in size. Under this trend, the height of a vent will have to be raised considerably since the height of a vent pipe is generally decided by a breadth of a corresponding vessel. Accordingly, we have initiated an examination to find an alternative method which can be used to determine the safe height of vent masts, instead of the current rule requirement. This paper describes the dispersion characteristics of boil-off gas spouted from a vent mast under cargo tank cool-down conditions in the membrane type LNG carriers.*

Key Words : *LNG carrier(Liquefied natural gas carrier), IGC code(International Gas Carrier Code), Gas dispersion, BOG(Boil-off Gas), CFD*

요 약 : 일반적으로 액체가스운반선은 인화성 화물이나 독성물질을 운반한다. 이러한 화물들은 폭발, 화재 및 인명손상을 가져올 수 있기 때문에, 액체가스운반선의 거주구역, 서비스 구역 및 통제실은 가스의 유입이 원천적으로 차단되도록 설계한다. 이러한 이유로, IMO IGC 코드의 멤브레인형 LNG선박의 화물탱크에 설치되는 벤트 출구의 높이는 노출갑판상 B/3 또는 6m 중 큰 것 이상으로 하고 작업구역 및 전후부 통행로, 갑판상의 저장탱크 및 화물설계 액위보다 6m 이상 높게 설치하여야 한다라고 규정하고 있다. 또한 LNG 시장이 점진적으로 증가하면서, LNG선박의 크기도 증가해 왔다. 때문에 현 규정에 의하면 LNG선박의 벤트의 높이는 선박 폭(B)에 비례하기 때문에 상당히 높아져야 할 것이며, 이는 높은 벤트 마스트(Mast)로 인하여 작업의 어려움 및 전방 시야를 방해하는 등 항해의 어려움을 초래한다. 본 연구에서는 멤브레인형 LNG선의 Sea-trial시에 측정하였던 데이터 및 CFD유동해석을 통해 LNG선박 화물탱크의 벤트 출구의 높이에 대한 적합성 평가를 수행한다.

핵심용어 : LNG선박, IGC code(산적액화가스운반선의 건조와 설비에 대한 국제규칙), 가스확산, 증발가스(BOG), CFD

1. Introduction

The LNG (liquefied natural gas) carriers have been designed, constructed and equipped to carry cryogenic liquefied natural gas stored at a temperature of －163 ℃ at atmospheric pressure. The liquefaction process reduces the specific volume of the natural gas by approximately 620 times, which allows large quantities of natural gas to be transported economically over long distances, primarily aboard large vessels.

In the event of an accident on an LNG carrier, it may easily vaporize and create a gas/air mix within the flammable range which is approximately between 5 to 15 vol% (about 50,000 to

---

[†] Corresponding Author : hkkang@krs.co.kr, 070-8799-8522

150,000 ppm). Liquefied gas carriers generally transport cargoes of flammable or toxic nature.

As known, the LNG market has been growing continually, which has led to LNG carriers becoming larger in size. Under this trend, the height of a vent will have to be raised considerably since the height of a vent pipe is generally decided by a breadth of a corresponding vessel. This, however, may cause following problems:

- Interference with watchers' vision under sail as shown in Figure 1
- Difficulties in installing and maintaining very large vent pipes of considerable height and diameter
- Reinforcement measures for hull deck
- Preventive measures against the vibration of vent pipes

Accordingly, this study specifically focused on identifying the dispersion characteristics of boil-off gas spouted from a vent mast under cargo tank cool-down conditions in the membrane type LNG carriers, and understanding the risk posed by the different gas leakages to propose the recommendations of safe height in vent masts that develop IGC code at IMO.

Fig. 1. Interference with watchers' vision under sail at the bridge of H. No.2258 built in DSME shipyard.

CFD has established itself as a valuable tool for risk assessment and safety analysis in process industries and design of new concept ships. Increasing use of the CFD is seen in evaluating the risk from dispersion applications in the coming years.

There are many literatures which reported the numerical studies on the natural gas release and dispersion. For the estimation of gas release rate, Dong et al.(2010) presented some simplified gas release rate models, based on the one-dimensional compressible flow equation.

Calculating accurately the leak rate from the vent is a perquisite to evaluate the hazard range of NG jet release.

The main objectives of the study are:

- to identify potential gas release scenarios
- create a 3-D modeling of the target ship
- examinate a CFD dispersion modeling of representative release scenarios measuring various environmental conditions, especially ventilating method
- evaluate the height of a vent required in IGC code

2. Methodology

2.1 Numerical Methodology

The numerical simulations of the fluid flow and heat transfer in the analyzed square duct geometries are conducted with the CFX 13.0 commercial code. For the working fluid, material properties of water are taken. Since the description of the basic conservation equations (mass, momentum and thermal energy) used in the code can be found in any classical fluid dynamics textbook or CFX manual, it is not repeated, here, but just explained the shear stress transport (SST) model.

The turbulence stresses and the turbulence viscosity μ_t were calculated with the transient shear stress transport model, which was developed and improved by Menter(1994). It is a combination of the κ-ε and the κ-ω model, where the turbulence eddy frequency is used as

$$\omega = \frac{\rho\kappa}{\mu_t} \tag{1}$$

At the wall, the turbulence frequency ω is much more precisely defined than the turbulence dissipation rate ε. Therefore, the SST model activates the Wilcox model in the near-wall region by setting the blending function F1 to 1.0. Far away from the wall, F1 is 0.0, thus activating the κ-ε model for the rest of the flow fields:

$$\text{SST model}=\text{F1}\cdot(k-w\ \text{model})+(1—\text{F1})\cdot(k-\epsilon\ \text{model}) \tag{2}$$

where the standard $k-\omega$ was first proposed by Wilcox as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k-\beta^{*}\rho k\omega \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + G_\omega - Y\omega+\left(1-F_1\right)D_\omega \tag{4}$$

And k-ε model was used by Launder and Sharma's model(1974). The SST model requires the distance of a node to the nearest wall for performing the blending between $k-\varepsilon$ and $k-\omega$. The wall scale equation is the equation solved to get the wall distance, simply:

$$\nabla^2\phi = -1 \tag{5}$$

where ϕ is the value of the wall scale. the wall distance can be calculated from the wall scale through:

$$\text{wall distance} = \sqrt{(|\nabla\phi|^2 + 2\phi)} - |\nabla\phi| \tag{6}$$

2.2 Initial and Boundary Conditions

The modeling of LNG gas dispersion released from the vent masts was carried out in the 3-dimensional LNG carrier. Figure 2 shows the general location of vent masts and its shape in LNG carriers.

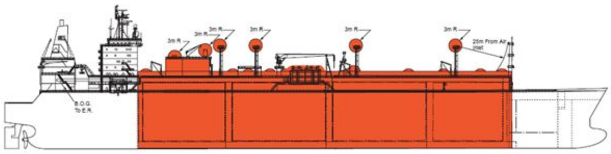


Fig. 2. Location of vent masts and dangerous zone in LNG carriers.

The time-dependent numerical simulations of dispersion of LNG gas were fulfilled with the commercial CFX code (ver. 13). The basic transport equations (mass, momentum and thermal energy) used in the CFX package are not repeated here as they can be easily found in any classical fluid dynamic book. Figure 3 illustrates the configuration and the mesh generation of a test section and Table 1 shows numerical details of the simulation.

On-board measurements in gas trial were also carried out to verify the modeling results. Figure 4 shows measuring points at No.2 Vent Mast of H.No.2258, which was built in DSME. The locations at which No.1 and No. 2 detectors were installed were 14

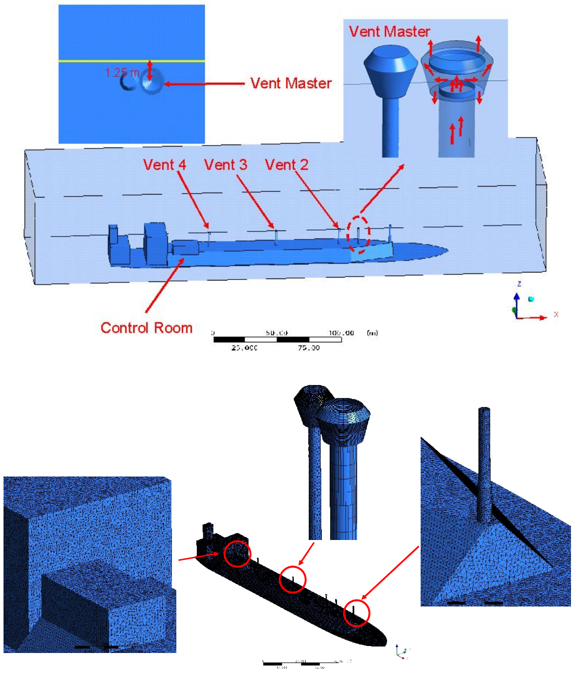


Fig. 3. Configuration of test section and mesh generation.

Fig. 4. Configuration of two detectors installed in No.2 vent mast of H.No.2258.

Table 1. Numerical conditions for the modeling

Domain	Grid	Fluid Model	Boundary Conditions	Numerical Setup
3-D	- Tetrahedron + Hexaheron : > 3.1x106nodes - Prisms smoothing: Solid walls	SST Model (Shear Stress Transport)	- Heading of ship: Air (5~8 m/s, 24~27℃, turbulent intensity =10%) - Outlet : 0 Pa - Top, bottom and both sides : Opening - Solid wall : no-slip, adiabatic - Inlet of vent riser : CH_4	- Advection scheme: upwind - Residual target : $< 10^{-5}$ - Residual type : RMS

meter and 12.5 meter high from the trunk deck respectively.

For each analyzed geometry, the optimized 3-dimensional grids were generated, taking into account the specific fluid flow conditions. Numerical grids were built with combined meshes of hexahedrons, tetrahedrons and prism, and the special care was taken to construct grids with sufficient resolution and uniformity because modeling results are generally dependent on grids. As the basic criterion for the grid resolution, the maximum non-dimensional wall distance y+ of the first layer of nodes was taken. In this study, the maximum y+ did not exceed the value of 10.0.

The computational domain for dispersion stretched from -200 to 200 m in the direction of the wind, from -40 to 40 m in the cross-wind direction and from sea level to 40 m elevation. The total grid cell count was approximately 3,100,000.

A dispersed gas can be recognized by two detectors installed in the No. 2 vent master to a certain threshold concentration, as shown in Figure 4(b). The concentration of the dispersed gas at a downwind distance from the release depends on the meteorological conditions including wind speed, wind direction and ambient temperature, ship speed and direction. Since the atmospheric conditions are constantly changing, it is impossible to assign a single value to those parameters and therefore the atmospheric parameters are used.

The environmental conditions (i.e., temperature and head wind speed) were 24 ∼ 26℃ with turbulent intensity of 10 % and 5 ∼ 13 m/s. The top, bottom and both side were set as the opening boundary condition and the outlet pressure was 0 Pa. The mass flowrate of leaks at the bottom of vent masts varied from 7620 to 8167 kg/h and a natural gas temperature was -74 ∼ -95℃. Table 2 shows measuring conditions of the cargo tank cool-down during gas trial and initial conditions for numerical simulations.

3. Results and Discussion

After setting the initial and boundary conditions and selecting appropriate models consistent with the physics of the dense gas dispersion, mass energy and momentum equations were solved in 3D space limited by the domain boundaries. The convergence criterion was set as the residual RMS becoming equal or less than 10^{-5}. After obtaining steady state wind and turbulence profiles at the start of the measurement the dispersion was simulated.

The dispersed range of NG released from a vent is influenced by many factors (e.g. LNG release rate and atmospheric environment, etc.). In this paper, the dispersion of methane gas was carried out for 5 different conditions: (i) cargo vapor pressure condition, (ii) cargo vapor temperature condition, (iii) different mass flow rate condition, (iv) wind speed and (v) atmospheric temperature condition.

Figure 5 shows the pattern of LNG gas dispersion actually observed in the LNG carrier(H.No.2258) at which the measurement was carried out during cargo tank cool-down conditions. There was observed that the environmental parameters (i.e., atmospheric stability and ambient wind speed) greatly affect the dispersion pattern and range of NG release through the turbulent mixing

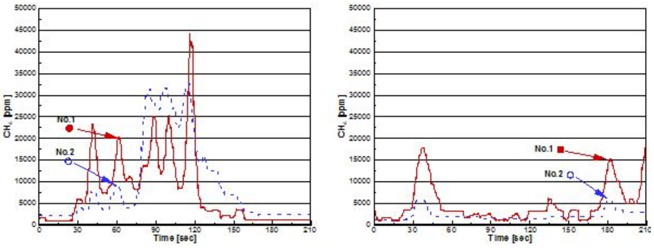
Fig. 5. Photo of LNG gas dispersion during gas trial.

Table 2. Measuring conditions at the cargo tank cool-down during gas trial and initial conditions for numerical simulations

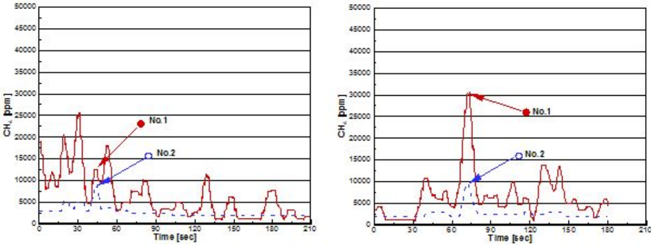
	Case I	Case II	Case III	Case IV
Cargo vapor pressure	1033 mbarA	1034 mbarA	1034 mbarA	1120 mbarA
Cargo vapor temperature	- 84℃	- 86℃	-74℃	-95℃
Mass flow at CH_4	7620 kg/h	7652 kg/h	7491 kg/h	8167 kg/h
Wind velocity	8 m/s	8.5 m/s	5.5 m/s	9.5 m/s
Weather	Sunny	Sunny	Sunny	Sunny
Ambient pressure	1016 mbar	1016 mbar	1015 mbar	1014 mbar
Atmospheric temperature	26 ℃	27 ℃	25 ℃	26 ℃
Wind direction	0 ∼ ±3°	0 ∼ ±3°	0 ∼ ±3°	0 ∼ ±3°
Humidity	64 %	64 %	64 %	64 %

between the gas and ambient air, but have little influence on the release rate of NG.

Prior to the simulations, on-board measurements of the gas concentration in No. 2 vent mast were conducted on existing concentration sensors on board. The sensor, with a preliminary test of measurement of CH_4, is applicable to measurement in the range of 0-100 vol%. The fluctuation in wind direction and wind speed results in the dynamic movement of the dispersed plume and variation in concentration at a certain downwind distance as shown in Figure 6. The concentration at a specific downwind distance depends on the discharge rate and the prevailing meteorological conditions at the point of release.

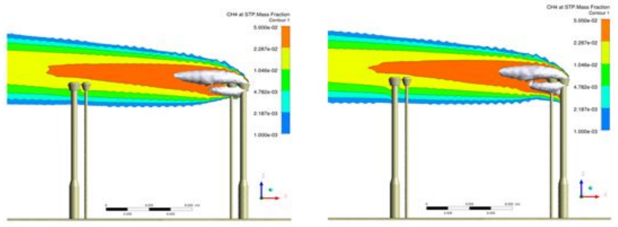


(a) Case I (b) Case II

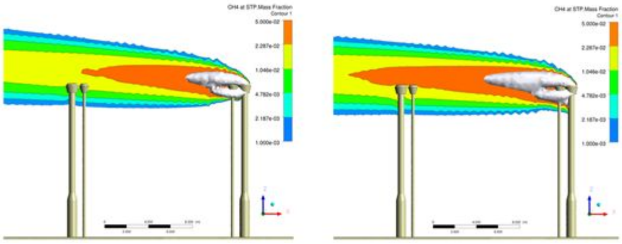


(c) Case III (d) Case IV

Fig. 6. Measured CH_4 variations for time traces at two different measuring points during sea trial.



(a) Case I (b) Case II



(c) Case III (d) Case IV

Fig. 7. Numerical results of LNG gas dispersion for 4 conditions at y = 0(center of ship).

Based on the concentration data obtained from the measurements, Figures 7 (a), (b), (c) & (d) illustrate the distribution of CH_4 with iso-contours during the dispersion of vented gas for four cases. The basic computational parameters for steady cases are listed in Table 2. After the dispersion, the density of CH_4 diluted quickly soon after gas dispersed toward No. 2 vent mast. The length and width of gas dispersion also show the increasing trend for the increase of mass flow at CH_4.

Figure 8 illustrates the comparison results of numerical simulations and on-board measurements. Lines on the graph represent the results of numerical simulation and symbols the measured values. The graph shows that the CH_4 concentration range of numerical simulations at No.1 sensor is approximately 17,000 ppm to 24,000 ppm and that of on-board measurements 14,000 ppm to 30,000 ppm. The simulation results of No. 2 detector were about from 500 ppm to 8,000 ppm and that of on-board tests 600 ppm to 10000 ppm. As one can see, the graph has the similar values when compared with the modeling results. Results from the gas dispersion show that the safe height of vent masts in LNG carriers is appropriate to the current requirements of paragraph 8.2.9 and 8.2.10 of IGC Code. As becoming larger in size in LNG carriers, however, the height of a vent will have to be raised considerably, since it is generally decided by the breadth (B)

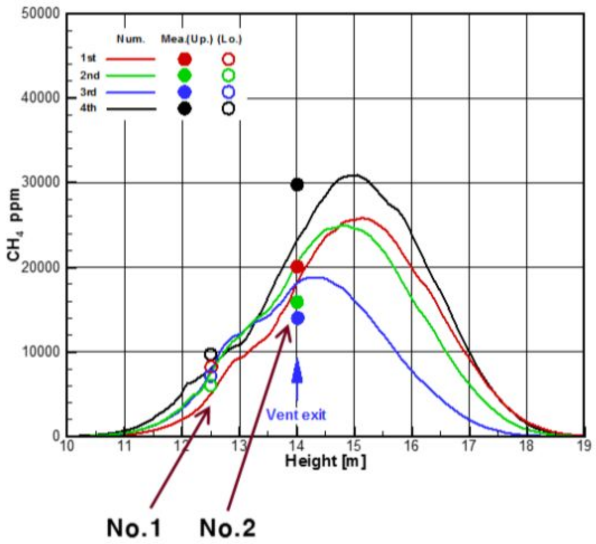


Fig. 8. Comparison of numerical predictions and on-board measurements.

of a vessel. Hence, more detailed considerations have needs to conduct the safe height of vent masts of ultra large LNG vessels in the coming years.

Based on Case IV, Figure 9 shows the concentration contours of the low flammable limit (i.e., LFL=0.05, color-coded according to gas concentration by volume) for the LNG gas release at 11, 12 and 13 m elevation, respectively, under the steady case when the ambient wind speed Ua=9.5m/s. One can see that the hazard range of gas release for the NG shows the prolate elliptical shape at all horizontal planes. At the plane of z=13.0 m corresponding to the source height (mast vent exit), the length of gas jet release reach the largest values when comparing with the cases of other horizontal planes.

Further, the length of gas release gradually decreases along with lowering vertical height. Therefore, the most hazard case of NG gas release in current conditions can be evaluated in the following context: the length of gas release, bounded by LFL=0.05 of NG, just at the lane of source height are taken as hazard range.(Havens, 1992)

As is widely recognized and also observed during experiments (Deaves, 1992), atmospheric dispersion of gases denser than air may involve several fluid flow regimes: buoyancy-dominated, stably-stratified and passive dispersion. During the simulation it was possible to observe all these fluid flow regimes. In the buoyancy-dominated regime, gravity-induced slumping and lateral spreading ensued until the kinetic energy of the buoyancy-driven flow was dissipated as shown in Figure 10. The dispersion then proceeded as a stably-stratified cloud embedded in the mean wind flow. The stable density stratification decreased as the dispersion proceeded, and the process approached a condition which represents a neutrally buoyant cloud embedded in the mean wind flow dispersing downwind (passive dispersion).

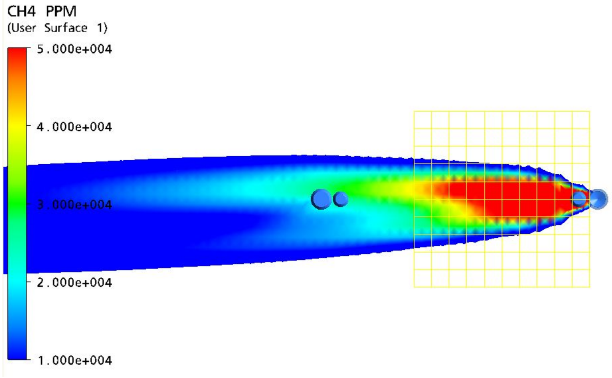


Fig. 9. LNG gas dispersion in the plane above 13 m from ground(wind direction –2 degree).

Fig. 10. LNG gas dispersion (air in: 5 m/s, CH_4 : 0.157 bar, 25 ℃ air).

4. Conclusions

Conclusions from the gas dispersion study show that the safe height of vent masts in LNG carriers is appropriate to the current requirements of paragraph 8.2.9 and 8.2.10 of IGC Code. Namely, In the current rule requirement of IGC code, the height of vent exits should not be less than B/3 or 6 m, whichever is greater, above the weather deck and 6 m above the working area, the fore and aft gangway, deck storage tanks and cargo liquid lines.

As becoming larger in size in LNG carriers, however, the height of a vent will have to be raised considerably, since it is generally decided by the breadth of a vessel. Hence, more detailed considerations have needs to conduct the safe height of vent masts of ultra large LNG vessels in the coming years. Moreover, the complexity of affecting parameters such as wind speed, venting speed, density of gas, etc, need to be considered and thus, it may be necessary to seek a way to define standard environmental conditions to obtain more accurate results.

References

[1] Deaves, D.(1992), Dense Gas Dispersion Modeling, Journal of Loss Prevention in the Process Industries, Vol. 5, No. 4, pp. 219-227.

[2] Dong, G., Xue, L., Yang, Y. and Yang, J.(2010), Evaluation of Hazard Range for the Natural Gas Jet Released from a High-pressure Pipeline: A Computational Parametric Study, Journal of Loss prevention in the Process Industries, Vol. 23, pp. 522-530.

[3] Havens, J.(1992), Review of Dense Gas Dispersion Field Experiments, Journal of Loss Prevention in the Process Industries, Vol. 5, No. 1, pp. 28-41.

[4] Launder, B. E. and Sharma, B. I.(1974), Application of the Energy-dissipation Model of Turbulence to the Calculation of Flow near a Spinning Disc, Letters in Heat and Mass Transfer, Vol. 1, Issue 2, pp. 131-137.

[5] Menter, F. R.(1994), Two-equation Eddy-viscosity Turbulence Models for Engineering Applications, AIAA Journal, Vol. 32, No. 8, pp. 1598-1605.

원고접수일 : 2013년 03월 14일
원고수정일 : 2013년 04월 12일
게재확정일 : 2013년 04월 25일