Observation on Effects of Liquid-Gas Density Ratio in Sloshing Pressure for LNG Cargo Design

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1 INTRODUCTION

Sloshing problems in marine engineering are mostly related to the design and operation of liquefied natural gas (LNG) such as LNG carriers, FSPOs, FSRUs, and bunkering vessels. Although computational methods for complex fluid flows are gaining popularity, prediction of sloshing pressure inside LNG tanks has relied on experimental measurements for several reasons. In the design stage of LNG tanks, experiments for estimating sloshing loads rely on model experiments at a scale of 1/50 to 1/30.

The problem with the model-scale experiments is that we cannot use actual LNG. Due to technical difficulties, sloshing model experiments are still conducted using water and air as media, and some research groups with advanced experimental facilities use water and heavy gas as media for model experiments. The experiment of filling gas with heavy gas is to match the density ratio of LNG and NG, that is, the density ratio of liquid and gas. Such studies have been introduced by Maillard et al. (2009), Ahn et al. (2012), Karimi et al. (2015), and Ahn et al. (2019). Recently, Lee et al. (2023) introduced a more advanced experiment using NOVEC 7000 material, and it is expected that this research is being continued with other materials.

This study aims to find the difference in sloshing pressure when applying the water-air combination and the water-heavy gas combination to the model for the tank shapes and motions of actual ships. If there is a specific ratio in the measured pressures in the two cases, it will be possible to apply such ratio to correct the results of water-air combination. This observation can be very useful in practice, because experiments using water-air are cheaper and have lower experimental uncertainty. To this end, the hydrodynamic pressures were analyzed for various models, loading rates, and motion conditions and the results of the two media combinations were compared.

2 KEY PARAMETERS FOR SLOHSING EXPERIMENT OF LNG CARRIER

Lee et al.(2023) summarized several non-dimensional parameters in sloshing flows, including the effects of liquid-gas density ratio and phase transition(Table 1). He showed that the magnitude of pressure peak is strongly dependent on the density ratio and impact duration is strongly dependent on phase transition. The main interest of this study is the density ratio of liquid and gas. Therefore, an appropriate material must replace air in order to match the same density ratio of LNG and NG.

Non-dimensional No.	Definition
Froude number	$Fr = U / \sqrt{gL}$
Euler number	$Eu = p / \rho U^2$
Mach number	$Ma = U / c$
Reynolds number	$Re = UL / \nu$
Weber number	$We = \rho L U^2 / \sigma$
Interaction index	$\psi = (\rho_{gas} / \rho_{liquid})[(\kappa - 1) / \kappa$
Jakob number	$Ja = (C_p \Delta T) / \Delta H$

Table 1. Non-dimensional parameters (All definitions are in Lee et al.(2023)

3 EXPERIMENT AND EXTREME STATISTICS OF IMPACT PRESSURE

The experimental technique is well described in several papers published by the authors, so a detailed description is omitted here. The data used in the analysis are the results of model experiments on actual ships conducted at Seoul National University over the past several years, and the ships are all large LNG carriers with the capacity range of 160,000~177,000 cubic meters. Fig. 1 shows examples of the model test for LNG tanks.

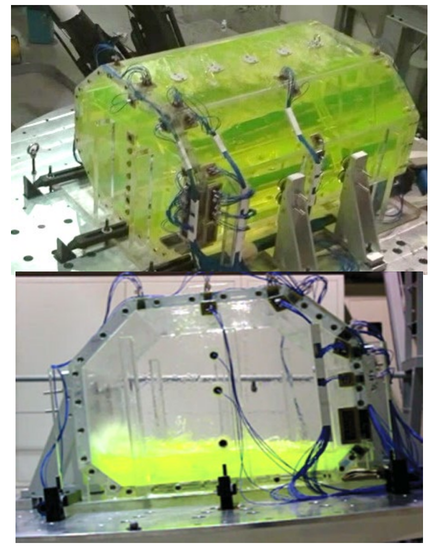


Figure 1: Examples of model-scale sloshing experiment for LNG carrier

The heavy gas applied in the experiment is a mixture of sulfur hexafluoride (SF6) and nitrogen (N2). The density ratio of the water-air combination is 0.001, but the density ratio of LNG-NG is 0.004. In order to have the density of heavy gas combined with water to have the same density ratio as LNG-NG, the ratios of SF6 and N2 are mixed at 56.9% and 43.1%.

In general, the load applied to the design of LNG tanks is applied using two analysis methods: short-term and long-term analyses. In short-term prediction, the measured impact pressure is sampled by moving the tank in irregular waves for a certain hours based on the actual ship for various sea conditions, and the pressure with a probability corresponding to 3 hours is obtained, and the design load is the largest pressure among the various conditions. The most popular extreme statistical probablity distribution of the sampled impact pressure is the 3-parameter Weibull distribution, which is expressed as follows:

$$f(x) = \frac{\gamma}{\beta}\left(\frac{x-\delta}{\beta}\right)^{\gamma-1} \exp\left(-\left[\frac{x-\delta}{\beta}\right]^{\gamma}\right) \quad (1)$$

where γ is a shape parameter, δ is a location parameter, and β is a scale parameter. Then the exceedance of 3-hour probability can be written as

$$P_{3-\text{hour}} = \delta + \beta\left\{\log\left(\frac{3}{D}N\right)\right\}^{\frac{1}{\gamma}} \quad (2)$$

where D is the hours of experiment and N is the number of measured samples.

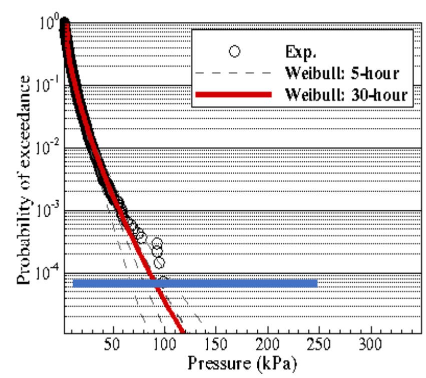


Figure 2: Example of Weibull distribution for short-term prediction

In long-term prediction, the size of the largest pressure is determined by probabilistically considering all sea conditions and operating conditions experienced by the ship. In other words, it is a method to estimate the maximum pressure value that can occur during the life-time of the ship by probabilistically combining the short-term prediction results of each condition. The design pressure for M-year life of ship can be obtained from the following equation:

$$P_{\mathrm{M}-y} = Q_{LT}^{-1}\left(\frac{1}{\left[\sum_{k=1}^{Fillings}\sum_{j}^{Headings}\sum_{i}^{Sea\ States} p_k p_j p_i E_{ijk}\right]\cdot(24)\mathrm{X}(365)\mathrm{X}(\mathrm{M})}\right) \quad (3)$$

where p_k, p_j, p_i are the probabilities of filling condition, wave heading, and sea state. In addition, E_{ijk} is the event rate which is defined as the number of impacts obtained per hour.

It should be mentioned that the predicted pressure value can change depending on the length of time for pressure sampling, whether it is a short-term prediction or a long-term prediction. Fig. 2 shows the extreme statistical distributions when the pressure sampled by performing the experiment for 5 hours in real scale is applied and when the sampled pressure data for 30 hours is applied. Naturally, the predicted pressure value converges as the time range increases, but a longer experiment costs more and takes more time. (Kim SY et al., 2022)

4 OBSERVATION ON EXPERIMENTAL DATA

The physics involved in hydrodynamic impact due to sloshing are very complicated, particularly when the interaction between liquid and gas plays an important role. Such observations were already introduced by several researchers such as Maillard (2009), Ahn et al.(2012) and Lee et al.(2023). For example, Fig. 3 shows the snapshopts of two different combination of water and gas: water-air and water-heavy gas.

Figs. 4 and 5 show the distributions of pressure peak obtained from experimental data and Weibull-distrihution fitting for two different LNG carriers with different filling conditions. As these figures show, Weibull dustribution provides reasonable fitting for the experimental data, and the different of pressure between water-air and water-heavy gas combination is obvious.

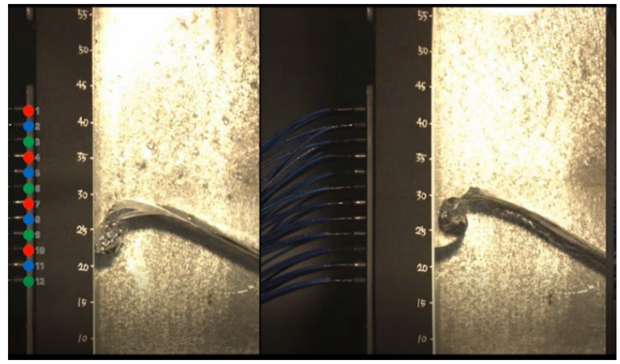


Figure 3: Snahshot of low-filling impact: water-air (left) and water-heavy gas(right) (Lee t al. 2023)

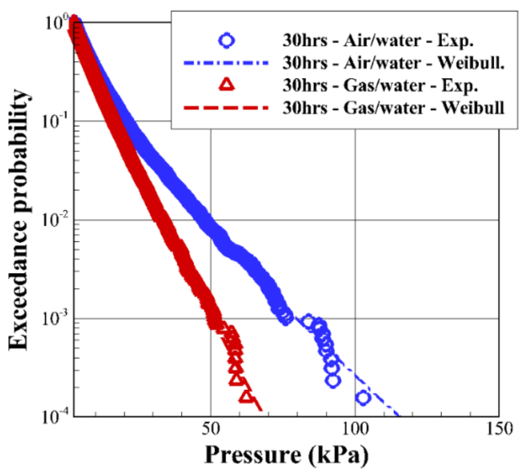
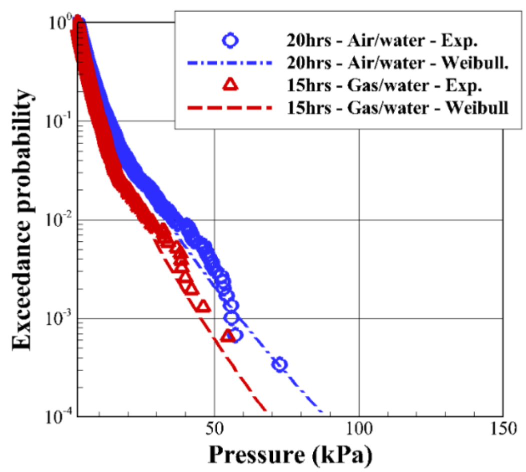


Figure 4: Exceedance probability in low-filling condition: 10% filling, Tank 1, 177K LNGC



Figre 5: Exceedance probability in low-filling condition: 30% filling, Tank 2, 160K LNG

Ship Capacity	Filling ratio (%)	P_{gas}/P_{air}
160K	10	0.69
	15	0.69
177K	10	0.61
	10	0.63
160K	30	0.69
	30	0.63

Table 2. Pressure ratio in low-filling conditions: short-term prediction for three ships

Table 2 summarizes the ratio of pressure of 3-hour short-term prediction for three different ships with low fillings. It is clear that the pressure values of water and heavy gas are in the raange of 60~70% of those of water and air combination. Table 3 shows the pressure ratios of a 160K LNG carrier in high-filling conditions. In general, the ratio in high filling condition is less than low filling, and it doesn' exceed 0.6. This means that the effects of gas property plays more important role during slohing impact occurrence on the tank ceiling.

Significant wave height (m)	Mean period (sec)	Pressure of short-term prediction (P/ρgL)		P_{gas}/P_{air}
		Water-Heavy gas	Water-Air	
9.5	7.5	3.56	7.47	0.47
12.5	9.5	4.00	7.02	0.57
15.5	11.5	3.53	7.24	0.48

Table 3. Pressure ratio in high-filling condition: short-term prediction, 160K LNGC, 95% filling

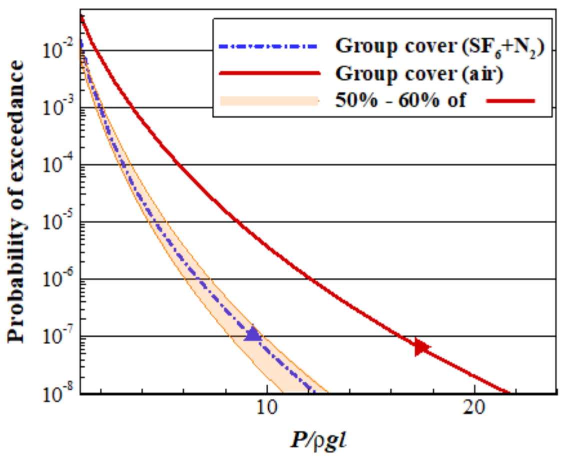


Figure 6: Exceedance probability in high-filling condition: long-term prediction 95% filling, Tank 2, 160K LNGC

Fig. 6 shows the collection of the result of long-term prediction for the 160K LNG carrier, which includes all the wave environmental conditions. Therefore, this result is the most important to estimate the design loads for LNG cargo containment system.

Similar to the short-term results, the long-term prediction based on the experiment using water and heavy gas is in the range of 50~60% of that of water and air. Therefore, if we apply a ratio of about 60% at high loading and 70% at low loading to the measured sloshing pressure by performing experiments on water and air, the values will not excced the experimental results on water and heavy gas. It should be noted that this ratio is only for the magnitude of pressure peaks, and the impulse duration is another concern.

5 CONCLUSION

In this study, the results of sloshing experiments using water-air and water-heavy gas were compared to estimate the sloshing design load of LNG ships, and the ratio of their pressure values was observed. From the results, it can be concluded that applying a ratio of 60% at high-filling condition and 70% at low-filling conditions measured in water-air experiment can be imposed to correct the effects of the density ratio of LNG-NG. These factors can be utilized for realistic ship design.

REFERENCES

[1] Ahn Y, Kim S.Y., Kim KH, Kim Y, Park J.J. 2012. *Density ratio of liquid and gas in sloshing experiment*. The 26th International Workshop on Water Waves and Floating Bodies, Copenhagen, Denmark.

[2] Ahn Y, Kim Y, Kim S-Y. 2019. *Experimental study and method of sloshing model test considering gas-liquid density ratio*. Int J Offshore Polar Eng 29, 257–68.

[3] Ahn Y, Lee J, Park T, Kim Y. 2023. *Long-term approach for assessment of sloshing loads in LNG carrier, part I: Comparison of Short- and Long-term approaches*. Mar Struct 89.

[4] Kim S-Y, Kim Y. Lee J. 2022. *Outlier analysis of sloshing impact loads on liquid ship cargo*, J Eng Marit Environ 236, 1-14.

[5] Lee J, Ahn Y, Kim Y. 2021. *Experimental study on effect of density ratio and phase transition during sloshing impact in rectangular tank.* Ocean Eng 242:110105.

[6] Maillard S, Brosset L. 2009. *Influence of Density Ratio Between Liquid and Gas on Sloshing Model Test Results*. Int J Offshore Polar Eng 19, 271–279.