Study on the Effect of Density Ratio of Liquid and Gas in Sloshing Experiment

Yangjun Ahn, Sang-Yeob Kim*, Kyong-Hwan Kim*, Yonghwan Kim*, Jong-Jin Park***
*Department of Naval Architecture and Ocean Engineering, Seoul National University,
Seoul, Korea
** Samsung Heavy Industry,
Goje, Korea

INTRODUCTION

Sloshing in LNG carriers can lead to large impacts on the containment system. It is important to assess these impact pressures and forces for adequate design of containers. Because of stochastic character of sloshing, experimental analysis is mainly recommended by ship classification societies (ABS, 2006; DNV, 2006). An experimental system for sloshing has been settled down in Seoul National University (SNU) to predict pressure impacts.

In the application of experiment analysis, how to scale the experimental results to the actual design is one of the difficulties. Dimensionless numbers for this application have been studied, but none of them have drawn a complete conclusion. Global behavior of the fluids is governed by the Froude number, so the ullage pressures should be Froude scaled (Bass et al., 1980). The local behavior, however, needs another scaling law.

To find out appropriate scaling law for local phenomenon of sloshing, analytic, numerical, and experimental studies have been conducted. Acoustic scaling including the density ratio has been theoretically identified, it is to be relevant as well as Froude scaling to the sloshing problem (Dias et al., 2007). During the impact, transfer of momentum between liquid and gas is occurred, so the density ratio has an influence on the impact pressure. Numerical studies have also shown this influence of the density ratio (Dias et al., 2007).

The consequences of experiments have substantiated the importance of the density ratio (Maillard and Brosset, 2009), and a dimensionless number, which consists of the density ratio and polytropic index, has been proposed with experimental results (Yung et al., 2009). Sloshing model tests at small scale which give the density ratio consideration is considered more representative. Model tests of previous studies, however, have been performed with 2D harmonic motions for reducing uncertainties of an experiment. Influence of the density ratio on sloshing is still unclear, and another parameter of sloshing experiments can be dependent on the density ratio. The density ratio, for example, could affect the resonance frequency, which is usually shifted with the experimental conditions from the theoretical approach.

This paper presents a variation of the sloshing loads with respect to the density ratio between fluids. 2D tank has been manufactured for finding appropriate resonance frequencies. Moreover, 3D tank and actual design sea conditions have been carried out, and the experimental results with different filling levels are illustrated in this study. The results of actual design conditions could be affected by secondary effects of the test conditions such as heading angles, sea conditions, 3D effects, and other parameters, the influence of the density ratio on the statistical pressure is still observed even in the irregular motions of the significant environment conditions.

SCALING LAWS and DIMENSIONLES NUMBERS

Several parameters including the density ratio have been proposed for sloshing problem, and they consider compressible phenomena. Nondimensional approach to the Navier-Stokes equation for homogeneous compressible flows is

$$\frac{\partial \Phi'_L}{\partial t'} + \frac{u'^2_L}{2} + \left(\frac{1}{Fr^2}\right) z' = \rho'_G \, \Psi \left[\frac{\partial \Phi_G'}{\partial t'} + \frac{u'^2_G}{2} + \left(\frac{1}{Fr^2}\right) z' \right] - \frac{1}{We}\left(\frac{1}{k'_1} + \frac{1}{k'_2}\right)$$

where $Fr = U / \sqrt{gD}$, $\Psi = \left(\bar{\rho}_G / \bar{\rho}_L\right)\left[(\kappa - 1)/\kappa\right]$, $We = \rho'_L U^2 D / \tau$, respectively (Yung et al., 2009).

Sloshing impact can be categorized by the magnitude of the fluid velocity u (Dias et al., 2007). According to this category, a homogeneous flow with mixture of liquid and gas hit the wall at the same speed, or otherwise separated flow give an impact on the wall with different velocities. These two types of flows need different scaling law, and they are

$$(\Delta p)_{S,SF} = \chi_1 \chi_2 (\Delta p)_{M,SF}$$

$$(\Delta p)_{S,HF} = \chi_3 (\Delta p)_{M,HF}$$

where

$$\chi_1 \equiv \frac{\rho_{vapor} c_{vapor} \lambda^{1/2} + \alpha(1-\alpha)\rho_{liquid}\sqrt{g} Fr \lambda L_M^{1/2}}{\rho_{gas} c_{gas} + \alpha(1-\alpha)\rho_{water}\sqrt{g} Fr L_M^{1/2}}$$

$$\chi_2 \equiv \frac{\rho_{liquid}}{\rho_{water}} \frac{\rho_{gas}}{\rho_{vapor}} \left(\frac{c_{liquid}}{c_{water}}\right)\left(\frac{c_{gas}}{c_{vapor}}\right)^2$$

$$\chi_3 \equiv \sqrt{\frac{\rho liquid}{\rho water} \frac{\rho gas}{\rho vapor}} \frac{c_{vapor}}{c_{gas}} \lambda^2$$

The subscript S refers to the real scale, M refers to the model scale, HF to the homogeneous flow, and SF to the separated flow (Dias et 마,, 2007).

The governing equation and those dimensonless numbers indicate that consideration of the density ratio is strongly required for prediction of sloshing impact. Therefore, in this study, the density ratio is considered as a parameter of sloshing experiment, and possible influences are observed.

EXPERIMENTAL SETUP

Motion Platform and Model Tank

The experiments were carried out in Seoul National University (SNU). On a motion platform, two model tanks have been mounted: 1/50-scale 3D model tank, and 1/40-scale 2D model. The motion platform, which has five ton capacity, is hexapod type consisting of six actuators. The 3D model tank is based on a membrane tank of 160K LNG carrier, and it has been design by Samsung Heavy Industry. The geometry of 2D model tank is given by Gaztransport & Techigaz SAs at the benchmark on sloshing model test.

The inner side of the 2D tank has a length of 946mm, a width of 118mm, and a height of 670mm on model scale. The test tanks were made of acrylic to enable visualization of the fluid motion inside of the tank and its thickness $35mm$ was used for preventing vibration of tank walls. Surfaces of the tank are flat, so invar edges or corrugations of an actual tank were not considered. Geometries of the tank are presented in Fig. 1 and the model tanks are shown in Fig. 2 and Fig. 3.

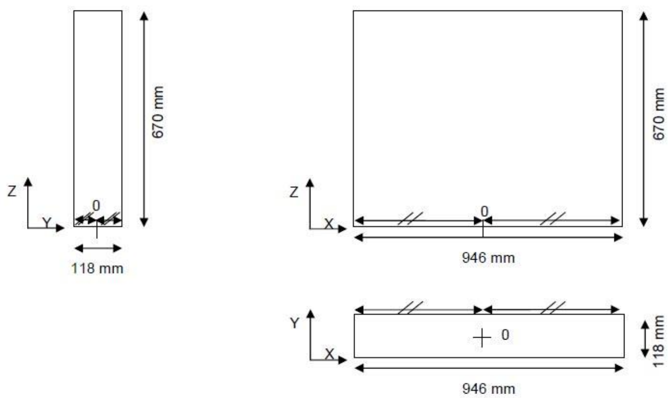


Fig. 1 2D model tank geometry

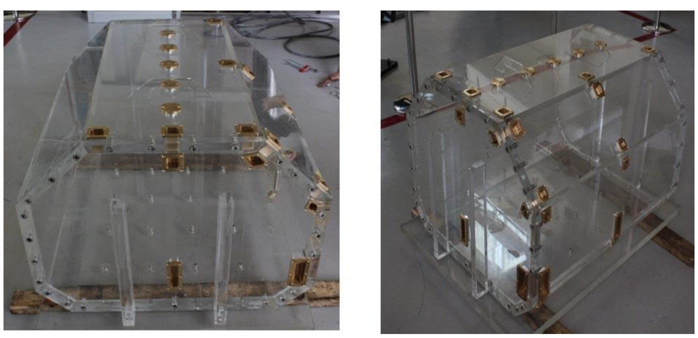


Fig. 2 3D model tank

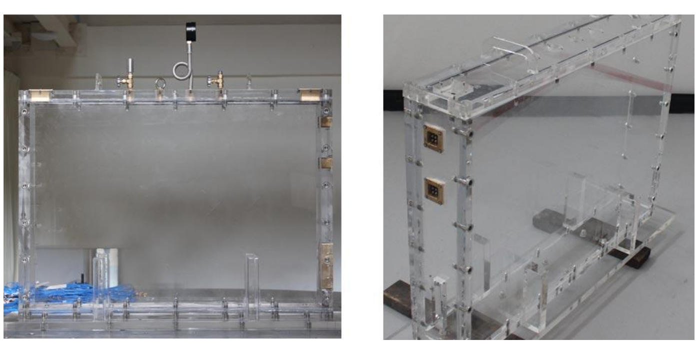


Fig. 3 2D model tank

Measuring System

Fig. 4 shows a simple diagram of experimental setup. Tank model is excited on the motion platform and sloshing impact pressures inside of the tank are measured by pressure sensors. A coupler adjusts the bias voltage of pressure signal to zero and the DAQ system converts the pressure signal to digital data with direct current coupling.

Sloshing pressures were measured with Integrated Circuit Piezoelectric (ICP) sensor (model: 211B5) made by KISTLER Co. The sensing diameter of this sensor is 5.54mm, and the maximum pressure range is 7 bars. The sensors were placed in a various arrays. The sampling frequency was fixed at 20 kHz which is suggested as in the reasonable range (Nitin et al., 2010).

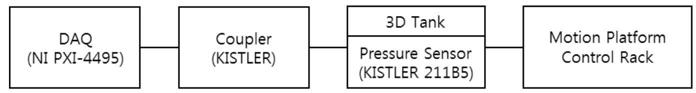


Fig. 4 Experimental setup

THE DENSITY RATIO VARIATION

Mixed gas properties

Water and air have been commonly used for sloshing model tests due to practicality. The density ratio of water and air, however, is different from that of natural gas (NG) and liquefied natural gas (LNG). The condition of the model test using water and air at ambient is physically different, so an alternative material is required instead of water or air at ambient to have similar density ratio between liquid and gas.

A mixture of SF_6 and N_2 replacing air was used as an alternative. The right proportion of these two constituents was used in the experiments for varying the density ratio, and water was used as it is. Properties of gas which were used are presented in Table 1.

Table 1 Gas properties

Products	Density (kg/m^3)	Ratio (%) of mixture
Sulfur hexafluoride (SF_6)	6.1620	56.9
Nitrogen (N_2)	1.1455	43.1
Mixture	3.9999	-

Procedure of gas injection

Tests were carried out with the completely sealed tank. To prevent losing gas from the tank, the water type silicon was used for sealing, and gas loss from the tank was checked with bubble at every test before and after. Pressure inside of the tank could influence on the result of the sloshing impacts, so a pressure gauge was manufactured for observing inside pressure. To make the target density ratio of each experiment, the oxygen level inside of the tank was checked instead of the level of mixture gas because of two reasons: the oxygen level required a less heavy tester than the sulfur hexafluoride level did; and oxygen has the second most proportion of air. The procedure of the gas injection and sealing tests are shown in Fig. 5.

Most gases including SF_6 and N_2, which were used in the experiments, are soluble. After the injection of mixture, gas which was dissolved in air inside of the tank had different density to that in water. This difference could change the density ratio while the experiments were conducting. Hence, water should be fully saturated with the gas in advance; therefore, the fluids inside of the tank were shaken to be mixed. One degree-of-freedom forced motion was performed with several repetitions until the oxygen levels were converged. The oxygen levels were also recorded before and after each test, and the density ratio inside of the tank was checked with this record.

TEST CONDITIONS

2D regular conditions

The resonance frequency equation, which is generally used, is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{\pi}{l}\, g \tanh\left(\frac{\pi h}{l}\right)}$$

and this is based on 2D approach. Moreover, because standing wave is the primary concern for this equation, breaking waves or hydraulic flows are not included. Amplitude of forced motion is also excluded, so the experimental results could varies with a lot of experimental conditions.
Based on the resonance frequency equation, the frequency of forced motion varies to find out the condition giving the largest sloshing pressure. Two different amplitudes of 40 mm and 15 mm are considered for different filling levels.

3D irregular conditions

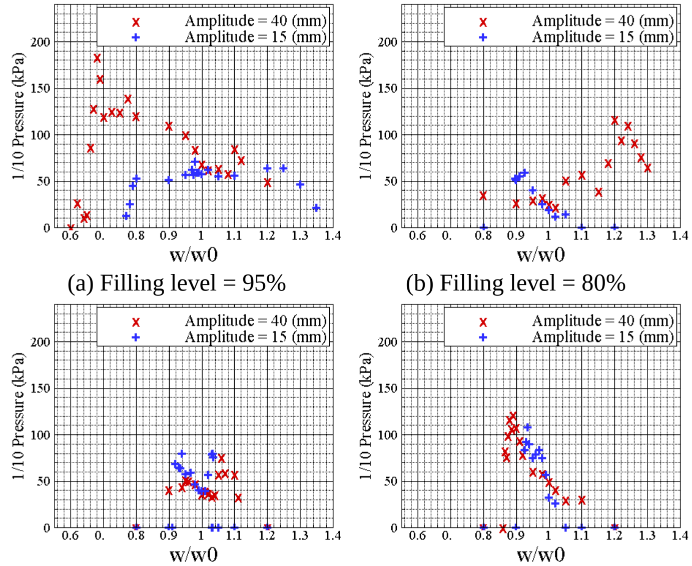
All the irregular test conditions have drawn from screening experiments. In the screening experiments, the significant wave height is considered as 40 years in North Atlantic Ocean for head and quartering seas, and 1 year for a beam sea. Sloshing pressures are measured during 36 minutes corresponding to 5 hours in real scale. The screening experiments, which covered various sea conditions, filling levels, and heading angles, led to the experimental results of sloshing pressures, and three conditions giving significant results were selected as the test conditions.
Each selected condition was repeated with five times of five different density ratios between liquid and gas inside of the model tank were derived for each test. Temperature and pressure inside of the tank were kept as a room condition, so the density ratio varies only with controlling the composition of gas.

EXPERIMENTAL RESULTS

The results from the post-processing of data are summarized in this part. Resonance tests have been being derived, and parts of them show the results which are away from the prediction. In the irregular conditions, sloshing impacts are occurred on the different tank faces according to the filling levels; therefore, the experimental results are categorized along the filling levels and tank faces.

2D regular conditions

Fig. 5 presents the 1/10 largest impact pressures of the 2D harmonic motions. The filling level is higher; distribution of the sloshing pressure tends to have wider bands. In the same filling condition, the magnitude of the amplitude does not indicate the certain shift direction of the largest impact frequency.
Complex phenomena have been observed in particular conditions. Sloshing impacts only occur on the one side of the tank in the regular motion of 70%H filling level with amplitude 40 mm and 0.948 Hz in model scale. The position which the impacts are observed switches its side depending on the initial mass movement of the liquid. Fig. 6 shows that biased impact locations appear although the experiments of (a) and (b) of Fig. 6 have been carried out in the same conditions.
Small differences of frequency give significant change of sloshing pressures. The frequency of (a) of Fig. 7, which is 0.8959 with the filling level 70%H and the amplitude 40 mm, is 0.0009 lower than that of (b). The sloshing impact, however, only occurs in the condition of (a) of Fig. 7.



(a) Filling level = 95% (b) Filling level = 80%
(c) Filling level = 70% (d) Filling level = 60%

Fig. 5 Measured sloshing pressure varying the excitation frequency

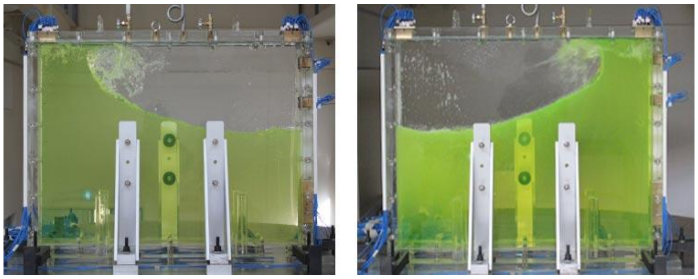


Fig. 6 Biased impact location at the same experimental conditions

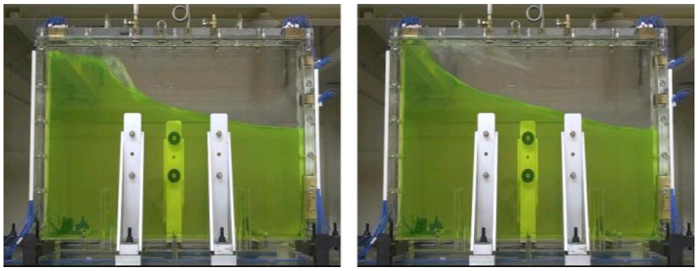
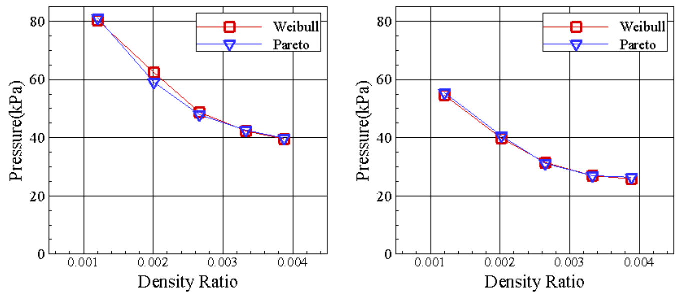


Fig. 7 Change of overall flow with small difference of frequency

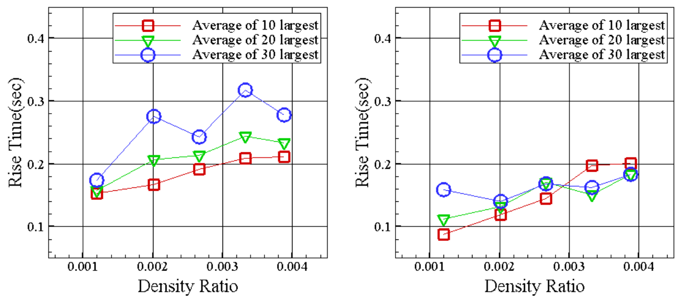
3D irregular conditions

The 3 hours extreme statistical pressures, which have been obtained by Weibull and Pareto schemes, are shown in Fig. 8. Tank top comes first for high filling conditions. The low filling level tests are not presented here, because no sloshing impacts have occurred on the tank top at the low filling tests. Fig. 8 indicates that the statistical pressures decrease approximately 50% as the density ratios increase from 0.0012 to around 0.004.
The density ratio is predicted to influence on pressure rise times. Since high sloshing impacts have been primary concerns, the average rise times of 10 largest, 20 largest, and 30 largest impact pressures are considered with respect to the density ratio. In the high filling experiments, global slowdowns of the pressure rise times have been recorded, and these results are presented in (a) and (b) of Fig. 9. Consideration of more impact signals distracts the trend of rise time; Rise time of fewer largest impacts is more clearly increase.



(a) Filling level = 95%H (b) Filling level = 70%H

Fig. 8 Influence of the density ratio to the statistical pressures on the tank top



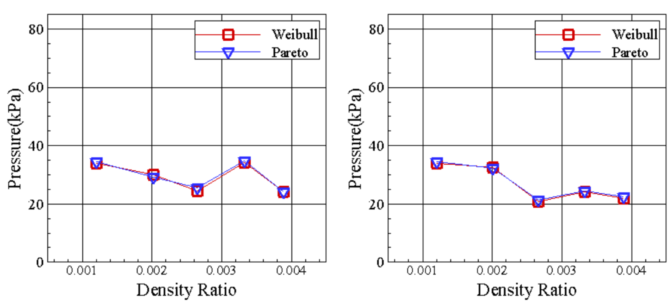
(a) Filling level = 95%H (b) Filling level = 70%H

Fig. 9 The average of rise time on the tank top – *n* largest pressures

Low filling level of irregular conditions

Every low filling condition was repeated twice to get more appropriate results. During the low filling tests, most of the sloshing impacts are occurred on the side wall. These statistical sloshing impacts on the side wall are shown in Fig. 10.

Although the tests have been repeated, some discrepancies are observed. In the first low filling tests, the highest statistical pressures are recorded when the test are performed with the density ratio around 0.0033. It is noticed that a weak trend of decrease in the second low filling test, but the graph shows an unpredicted result around 0.0033 density ratio.



(a) Filling level = 10%H (case 1) (b) Filling level = 10%H (case 2)

Fig. 10 Influence of the density ratio to the statistical pressures on the side wall

CONCLUSIONS

The experiments draw the conclusions that the sloshing impact varies as the density ratio is changed. Mixed gas of SF_6 and N_2 has been injected, and an experimental procedure with completely sealed 2D and 3D tanks has been proposed for varying the density ratio. Some conclusions are made as follows:

- In the irregular conditions, the high filling conditions show more significant changes and the obvious trend through the experiments while the low filling conditions do not show such clear results.
- Between large impacts of each test case, it is observed that rise time increases as the density ratio does. The magnitude of its change is more obvious in the experiments of high filling conditions than in those of low filling conditions.
- While the sloshing impact pressures is extremely varied between a density ratio of 0.0012 and 0.004, the rate of the change of pressure decreases as the density ratio approaches to that of actual LNG cargo tank.
- Location occurring sloshing impact on relates to the experimental conditions; the density ratio might have an influence on the location of the impact.
- The most significant sloshing impacts would not occur at the resonance frequencies of the model tanks, and their frequencies are to be shifted. Sloshing impacts are sensitive to the frequency of tank motion, and influence of the density ratio on the resonance frequency is not yet identified.

In the experiments, it is hard to satisfy the conditions having the exactly same density ratio as the conditions of actual LNG cargo tank. Because small magnitude of density is dealt with, the density ratio of liquid and gas is very sensitive to the environmental conditions such as room temperature or pressures inside of the tank during the experiments. However, if the sloshing impact pressure in the experiments would be converged and become less sensitive in some specific region of the density ratio around 0.004, the experiments will be easy to be handled.

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