Experimental Study of Phase Transition in Sloshing-Induced Impact in Two-Dimensional Tank

Jeoungkyu Lee, Yangjun Ahn, Jieung Kim and Yonghwan Kim*

Department of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, Korea

*yhwankim@snu.ac.kr

1 INTRODUCTION

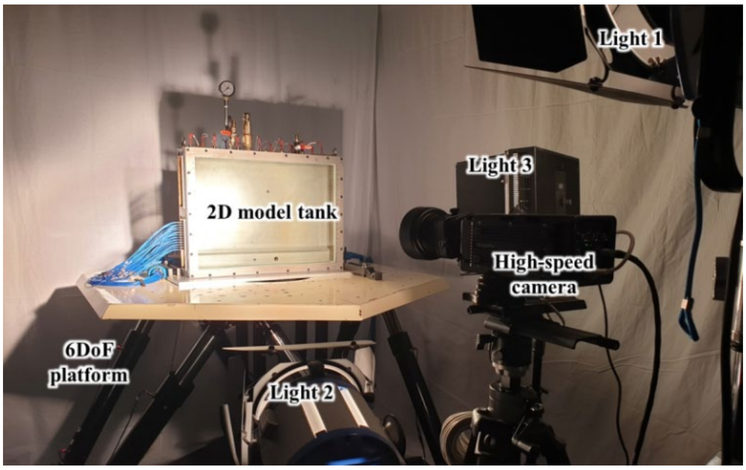
In the sloshing phenomenon, a lot of experiments have been conducted in terms of high nonlinearity and time cost in numerical method. Most sloshing experiments are performed with water and air, which has caused some challenges like density ratio and phase transition. In case of density ratio, the experimental method was improved by matching the actual density ratio between liquefied natural gas (LNG) and natural gas (NG) using the mixed gas. Dias et al. (2007) showed the influence of the density ratio with numerical approaches, and Ahn et al. (2012) studied the experimental analysis of sloshing phenomenon considering gas-liquid density ratio by performing 2-dimensional regular test and 3-dimensional irregular test. Karimi et al. (2015, 2016, 2017) investigated the effect of ullage gas on sloshing in terms of global and local flows.

Mailard and Brosset (2009) studied the effect of density ratio on sloshing impact for various gases including vapor. Experiment with vapor showed that condensation brings a reduction in impact compare to experiment with non-condensable fluids. Braeunig et al. (2010) showed that the oscillation is disappeared and the maximum pressure is strongly reduced, when the phase change is active. Kim et al. (2016) conducted drop tests by focusing on basic phenomena to investigate the effect of phase transition on impact pressure.

In the vicinity of the boiling point, the density ratio of water and vapor is significantly lower than that of LNG and NG. In addition, in the case of the sloshing experiment near the boiling point using water, it is difficult to observe the shape of flow generated at the impact due to the water vapor. Therefore, in this experiment, a sloshing experiment is conducted using NOVEC7000, which boils at 34 °C and has a density ratio of liquid and gas closer to the density ratio between LNG/NG than that of water and air. Single impact experiments are performed at low filling level. The impact pressure synchronized with the high speed camera is used to compare and analyze the difference in flow during the sloshing impact near the boiling point.

2 EXPERIMENTAL SETUP

Unlike conventional acrylic tanks, a stainless steel rectangular tank that can be heated is designed. A heating rod is installed at the rear of the tank to enable heating according to the depth, and the front is made of tempered glass to observe the flow. The rectangular tank is 630.7mm long, 78.7mm wide and 446.7mm high. The tank is mounted on a platform capable of 6 degrees of freedom movement and exerted motion in a surge direction.



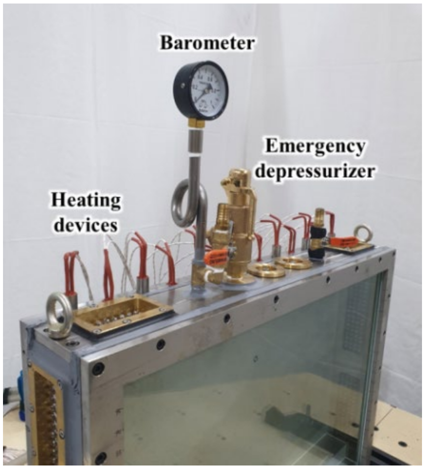


Fig 1. Experimental setup (left) and devices (right)

The dynamic pressure sensor (211B5 from KISTLER) is measured at a sampling rate of 20000Hz, and the sensors are arranged in 12 rows and 4 columns. The high-speed camera (Y4-S2 from Integrated Design Tools) mounted at the front is photographed at 4000 frame per second and synchronized with the measured pressure by the post-processing work. The liquid used in the experiment was NOVEC 7000, with a boiling point of 34°C at atmospheric pressure. The liquid density is 1400kg$/m^3$, the density ratio liquid to gas is about 0.0041, and the kinematic viscosity is 0.32cSt. In order to maintain the boiling point at 34°C, the ullage pressure is set to 1atm. The characteristics of the fluids used in the experiments are summarized in Table 1.

Table 1. Characteristics of the liquid

Liquid type	Density ratio	Kinematic viscosity (cSt)
Water (25°C)	0.0012 (water/air)	0.8917
NOVEC7000 (25°C)	0.0041	0.32
NOVEC7000 (34°C, boiling point)	0.0057	0.278

The experiment is carried out at 15% filling level and the pressure for single impact is measured by sin motion. The experiment using water was performed at room temperature, and the experiment using Novec7000 was performed at room temperature (25°C) and boiling point (34°C). In order to observe the impact of flip-through type, the magnitude and frequency of motion is 50mm and 0.631, respectively. The experiment is repeated 5 times for each experimental condition.

3 RESULTS

Experimental results according to liquid type and temperature are shown in fig. 2 and 3. Fig. 2 shows the flow at time t_0 when the maximum impact pressure occurs and the flow 0.05 seconds before t_0. In fig. 2, the symbols and numbers on the left represent each row of sensors installed in 12 rows and 4 columns, and the measured impact pressures in the corresponding rows are summarized in fig. 3. The measured impact pressure is normalized by the density of the fluid, the acceleration of gravity, and the height of the tank.

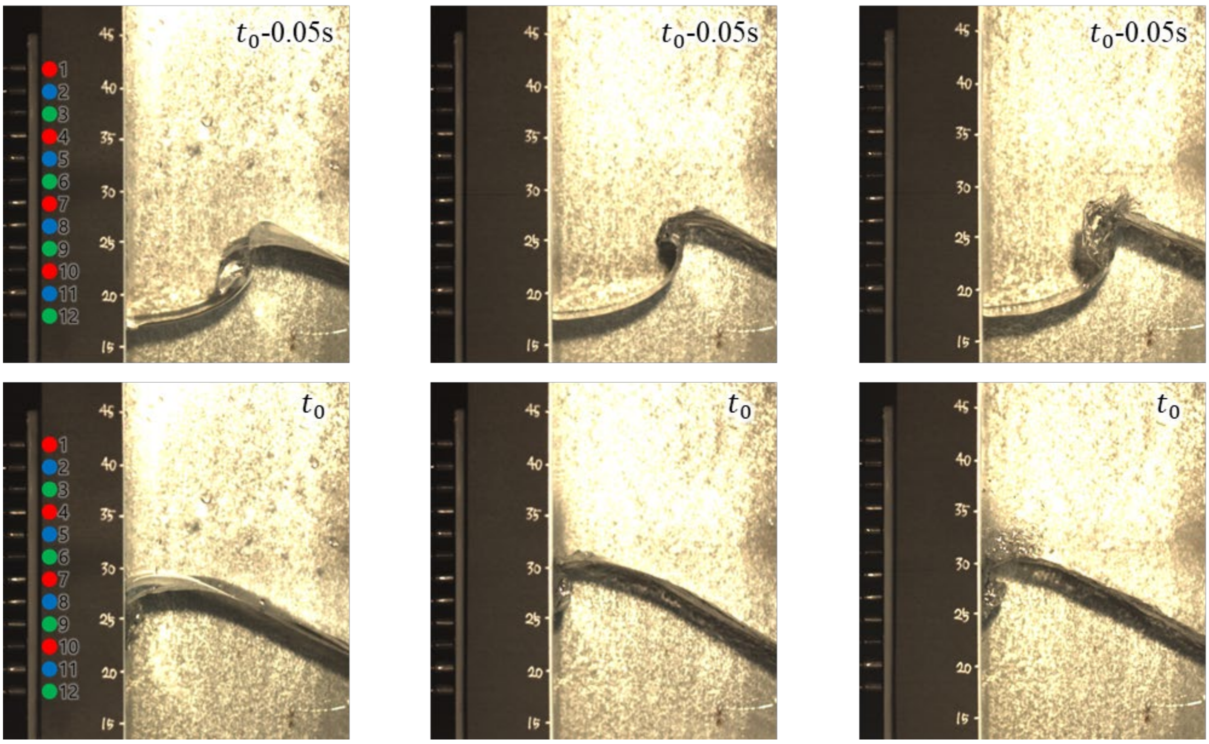


Fig 2. Images of single impact: Water at 25°C (left), NOVEC7000 at 25°C (middle), NOVEC7000 at 34°C (right)

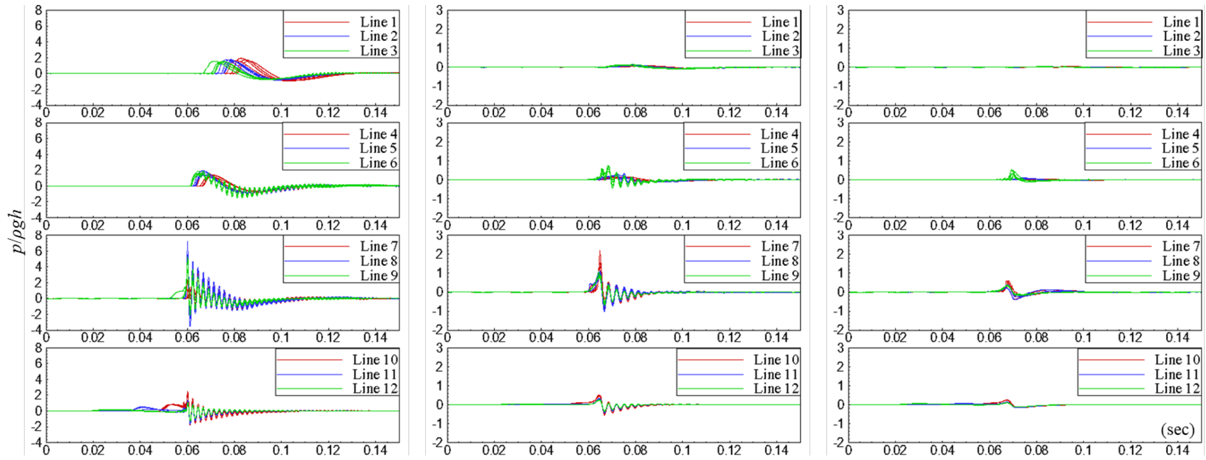


Fig 3. Measured impact pressure: Water at 25°C (left), NOVEC7000 at 25°C (middle), NOVEC7000 at 34°C (right)

Comparing the experimental results of water and NOVEC7000, as the density ratio increases, it delays breaking of the leading wave, which is the same trend as experimental result in Karimi et al. (2016). In the case of the NOVEC7000 at the boiling point, the density ratio is higher than room temperature, but due to the instability of the fluid near the boiling point, the front of the wave breaks and approaches the wall. In fig. 3, impact pressures occur sequentially from line 12 to line 1, with the highest impact pressures observed in lines 7, 8, and 9. As the density ratio increases, the impact pressure decreases as the kinematic energy of the wave decreases before impact occurs due to heavy gas. As the viscosity increases, the impact pressure decreases (Zou et al., 2015), but even though the water viscosity is higher than that of NOVEC7000, the impact pressure is higher, so the effect of density ratio can be considered to be more dominant in this experiment.

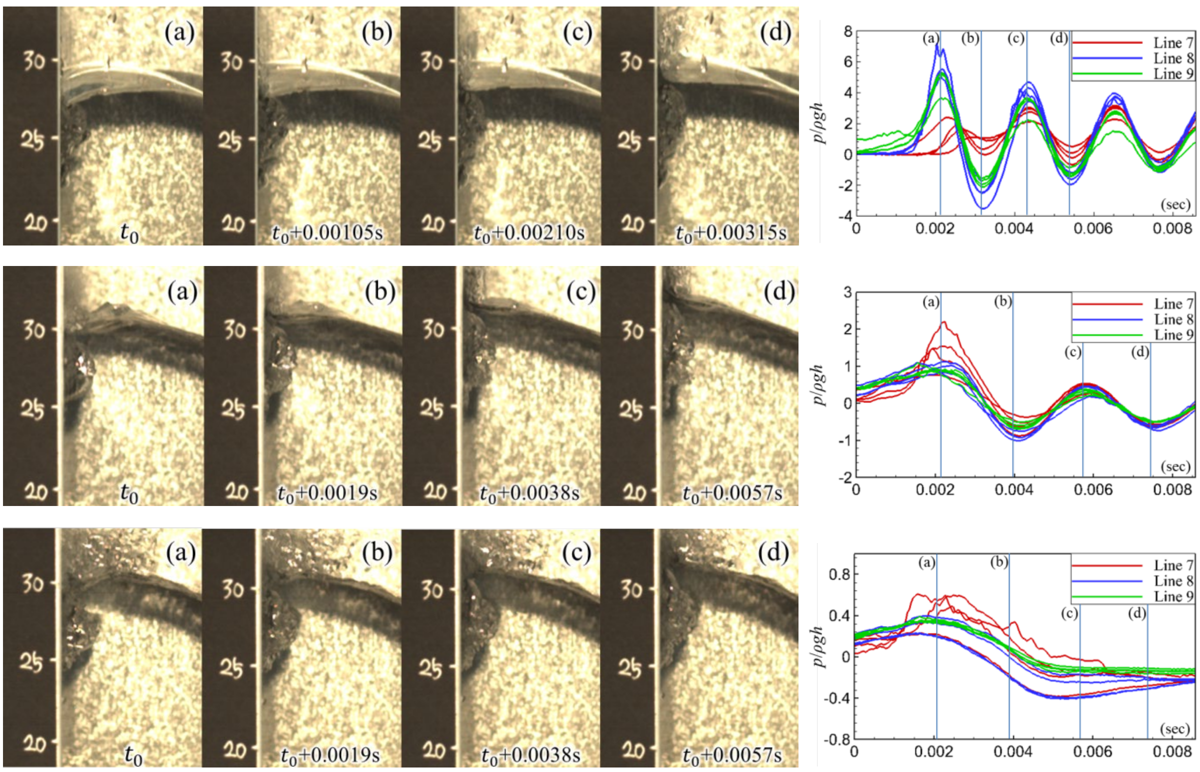


Fig 4. Changes of air pocket over time: Water at 25°C (top), NOVEC7000 at 25°C (middle), NOVEC7000 at 34°C (bottom)

Images synchronized with the impact pressure at lines 7, 8 and 9 are shown in fig. 4. The time scales are all the same and rearranged from zero seconds. In the experiment using water at room temperature, oscillation of 950Hz appeared at the impact pressure, and the oscillation of 530Hz occurred in the experiment using NOVEC7000 at room temperature. In fig. 4, the impact pressure signal decreases from crest to trough and the bubble size increases and then decreases as the impact pressure signal goes to crest. Peak pressures occur when gas pocket is compressed and negative pressures occur when gas pocket is expanded. However, in the case of the experiment using NOVEC7000 at the boiling point, after the gas pocket is generated, the impact pressure decreases after the peak as the gas pocket expands ((a)-(c) section), and the volume of gas pocket remains almost unchanged and the pressure is maintained in the (c)-(d) section. As the gas pocket compresses, pressure is applied to the gas near the boiling point, which causes a phase transition and decreases the amount of gas inside the gas pocket, so the power to expand is lost and the oscillation is reduced. In addition, since the compression effect is reduced as part of the gas pocket condense, the maximum impact pressure is also reduced.

4 CONCLUSIONS

Following conclusions can be made through out this study:

- As the density ratio increases, it delays breaking of the leading wave and the magnitude of the impact pressure decreases.
- The oscillation is reduced due to the phase transition in the impact with gas pocket near the boiling point.
- The phase transition reduces the maximum impact pressure at the boiling point.

ACKNOWLEDGEMENT

This study was supported by the Lloyd's Register Foundation (LRF)-Funded Research Center at Seoul National University. All of the supports are greatly appreciated.

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