Global and Local Effects of Gas-Liquid Density Ratio on Shape and Kinematics of Sloshing Waves and Scaling Considerations

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Highlights

- The effects of gas-liquid density ratio (DR) on sloshing wave shapes were investigated globally (far from impact zones) by 2D sloshing model tests with irregular excitations at two different scales and for low-fill levels. Such effects appear to be small for the tested range of density ratios which implies similar wave shapes far from impact zones,
- When repeating the same irregular motions, global flow keeps the same phase regardless of tested DRs which enables to recognize an accurate impact-by-impact relation between model tests at similar and different scales and adds a deterministic side to post-processing model test results,
- The local effects of DR (right before impact) on breaking wave shapes were also investigated by 2D sloshing model tests with single breaking waves at two different scales and for low-fill levels. The local effects of DR clearly modify the impact geometry before gas compressibility interference with significant consequences on induced pressures.

1 Introduction

Gas-liquid density ratio (DR) defined as, $DR = \frac{\rho_g}{\rho_l}$ where ρ_g is ullage gas density and ρ_l is liquid density, is a dimensionless number of interest in studying sloshing wave impacts and induced pressures. So far the importance of DR for sloshing has been investigated by analytical works, numerical simulations, and sloshing model tests. A few studies have concluded that DR has no significant effects on impact pressures (see Lee et al (2007)). On the other hand other numerical works such as Braeunig et al (2009) and Scolan et al (2014) and all the experimental studies so far concluded that DR is of importance (see Maillard and Brosset (2009), Yung et al (2010), Ahn et al (2012)). Results from Braeunig et al (2009) and Maillard and Brosset (2009) contributed to the adjustment of methodology proposed by GTT for sloshing assessment in tanks of membrane LNG carriers according to Gervaise, de Sèze and Maillard (2009). Results of Yung et al (2010) contributed to the assessment methodology presented by Kuo et al (2009). Both methodologies are based on sloshing model tests with Froude-scaled excitations and the same DR as full-scale. The DR similarity requirement is fulfilled by use of a heavy gas and water inside a model tank. It is accepted that DR plays an important role as higher density ratios (by keeping the same liquid) lead to less severe impacts and lower density ratios are associated with more violent ones. A few comments can be made on the former studies :

- All the mentioned experiments were done at one scale yet the results addressed scaling issues. Numerical works consider different scales but for simplified geometries and simplified liquid and gas properties,
- Experiments designed to study the effects of DR, mixed the effects of DR and gas compressibility and attributed them only to DR,
- The experiments do not discuss effect of DR on wave impact geometry which is crucial for the resultant pressures.

It seemed necessary to :

- Perform model tests at two or more scales,
- Try different density ratios at each scale,
- Have a high density of pressure sensors near impact zones,

– Have very accurate synchronized comparisons of visual and measured data,

And also to study impact geometries it was necessary to,

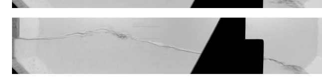
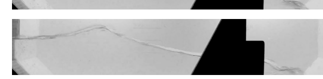
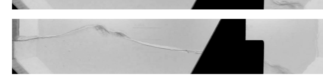
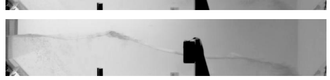
– Pay attention to the evolution of impact geometries far from impact zones until the moment of impact.

For addressing these requirements 2D sloshing model tests with 3 DOF irregular motions and 1 DOF sway motions (for generating single breaking waves) at 2 different scales of 1: 20 and 1: 40 were performed by GTT. Using two liquids of water and a solution of sodium polytungstate (SPT with density of 1800 kg/m^3) and different ullage gases of helium, air, two mixtures of SF_6 and N_2 (Mix_2 with a density of 2 kg/m^3 and Mix_4 with a density of 4 kg/m^3), and pure SF_6 enabled to verify a range of DRs at two scales. For model tests at scales 1: 20 and 1: 40, 252 and 120 PCB sensors were used respectively, installed symmetrically on two vertical tank sides. Each sensor sampled at 40 kHz. To have a more global view of fluid flow, a high-definition camera was utilized recording at 25 fps. In order to have accurate close ups at impact locations, Photron and Phantom high-speed cameras were used respectively at scales 1: 20 and 1: 40, recording at 4000 fps. Froude similarity was the basis for defining the scaled tank motions. All the tests were performed with atmospheric ullage pressure. Irregular tank motions helped to study global effects of DR on shape and kinematics of sloshing waves. Short 1 DOF sway tank motions generating repetitive single breaking waves provided knowledge on such effects locally. The term global implies the DR effects far from wave breaking locations where gas compressibility does not play a role. The term local on the other hand implies such effects near wave breaking locations and before impacts up to a point when compressibility is also influential. This point was detected by monitoring measured impact pressures.

2 Global Effects of Density Ratio

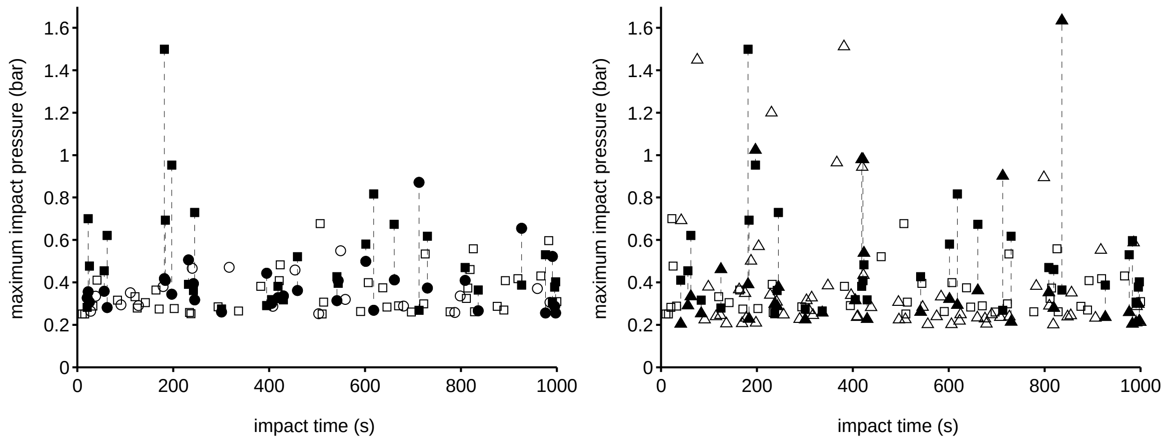
Sloshing wave shapes were monitored using an HD camera for the duration of irregular tests at both scales. Wave shapes were similar regardless of DR or scale with small differences. Such differences were also observed when comparing two repetitions at the same scale with the same DR. Furthermore flow kept the same phase regardless of DR or scale. There were no accumulation of residual differences due to local effects of using different gases and liquids. The global effects of DR on wave shape were small whereas such global effects on wave phase were negligible. Table. 1 illustrates the aforementioned observations by a comparison of liquid free surface for five repetitions of the same tank motions at a random time (t_r) at scale 1: 20 with multiple DRs as well as five repetitions of the scaled tank motions at time ($t_r/\sqrt{2}$) at scale 1: 40 with various DRs.

Table. 1 – Free surface with the repeated and scaled tank motions and different DR at the time t_r at scale 1: 20 and time $t_r/\sqrt{2}$ at scale 1: 40

Scale 1 :20				Scale 1 :40			
Liq.	Gas	DR (-)	Free Surface at $t = t_r$	Liq.	Gas	DR (-)	Free Surface at $t = t_r/\sqrt{2}$
SPT	air	0.0006		Water	He	0.0002	
SPT	Mix_2	0.0011		Water	air	0.0012	
Water	air	0.0012		Water	air	0.0012	
Water	Mix_2	0.0020		Water	Mix_2	0.0020	
Water	Mix_2	0.0020		Water	SF_6	0.0060	

2.1 Coincident Sloshing Impacts

The observation of in-phase fluid flow regardless of tested DRs and scale provided a basis for a more deterministic comparison of wave impacts at different model tests. Based on this observation if the model tank motions are exactly repeated (or scaled and repeated), wave impacts should be occurring at the same instants for all the repetitions regardless of DR and scale. This was investigated by comparing the recorded wave impact times for the repetitions of the same irregular motions at the same scale or at different scales while changing DR.



(a) (b)

Fig. 1 – Corresponding wave impacts with different density ratios at (a) scale 1: 20 and (b) scale 1: 20 and 1: 40.(□ : $DR = 0.0012$ at scale 1: 20 , ○ : $DR = 0.004$ at scale 1: 20, △ : $DR = 0.0002$ scale 1: 40. Filled markers indicate common impacts)

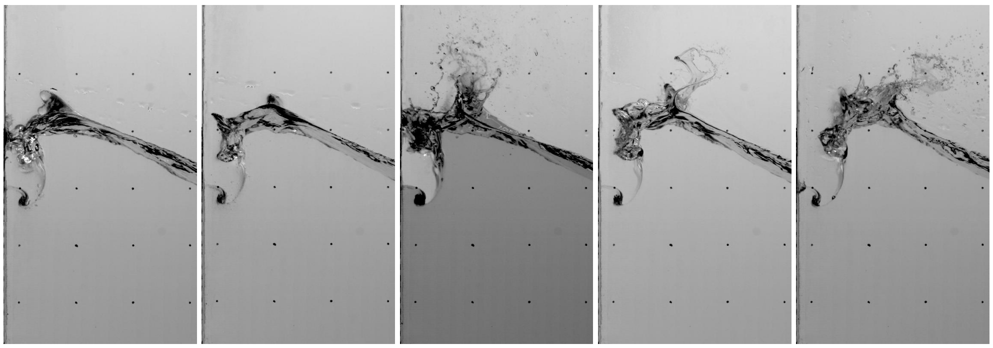
During the tests only impacts with maximum pressures higher than a threshold were recorded and the less severe impacts were filtered (this is common practice for standard sloshing model tests). Wave impact times were defined as the moments when the measured pressure by any pressure sensor on the sensor module exceeded the threshold. In order to compare the impact times of any two tests with the same (or scaled) tank motions, the wave impact times of one test were taken as reference times as $t_{i,ref}$ with i varying from 1, corresponding to the first recorded impact up to n, the number of the last recorded impact for the reference test. A time window as Δt_{ref} was defined around the reference impact times defining n time slots as $t_{i,ref} \pm \Delta t_{ref}$ and for the second test it was checked whether the impact times lie in the defined time slots. A coincidence was accepted only if it was impact by impact, i.e. if two or more impact times of the second test lied in the time slots defined by the reference test, they were rejected. In the performed comparisons, number of coincidences did not vary significantly with time windows larger than around 80 ms and dropped after a certain limit due to the criterion that was defined before. Furthermore after applying a small time shift ($100 - 200$ ms) to the impact times of one test in a comparison, number of coincidences dropped to almost zero indicating the non-random nature of coincidences due to the unique impact times governed by global flow.

The comparisons confirmed the idea of coincident and corresponding impacts at different tests regardless of DR and scale as shown in Fig. 1. Not all the measured impacts are found to have corresponding impacts at the other tank motion repetitions. This is mainly because of the filtering of some impacts due to the threshold. Stochastic nature of sloshing impacts causes large variations of the resultant pressure. Some of these impacts are filtered in each repetition due to such effects. Changing the gas also causes local changes which affect the resultant pressures and might lead to filtering for some impacts. Furthermore coincidences of events have also been separately investigated by 3D tests with 6 DOF irregular motions for high fills at two different scales (1: 25 and 1: 40), confirming the results of 2D tests. According to the observation, a perfect correlation between the impact times should theoretically exist.This enables to :

- Give each wave impact at full-scale an index which is defined by its unique impact time. The corresponding wave impact can be tracked down in model tests,
- Add deterministic aspects to sloshing model tests and their post-processing which is now solely statistical and reevaluate the current sloshing assessment methodologies by comparing full-scale impacts with the corresponding model-scale ones.

3 Local Effects of Density Ratio

A clear influence of DR on statistical pressures has been observed by many authors, as mentioned in the introduction. From the irregular tests, we could not notice any systematic influence of DR on the wave shapes that could explain that result. But irregular tests could be inappropriate to capture the trend as even repeating the same conditions induced small differences on the wave shape. Therefore, single breaking waves were generated by one period of harmonic sway motions of the tank. Trying different motion amplitudes and frequencies enabled to create a range of breaking wave shapes from mild slosh to broken waves with intermediate gas-pocket and flip-through conditions. The evolution of breaking wave shapes before impact was studied for each motion with different density ratios (see Fig. 2). The pressure sensors recorded pressure variations during such evolution to detect any compressibility effects. The local effects of DR, earlier than any interference from gas compressibility effects were detected. The local effects are such that smaller DR favors wave breaking and the wave front is more curved towards to breaking point. Larger DR on the other hand shows more resistance against the wave front. DR evidently changes the breaking wave shape and geometry which is a key factor influencing the induced pressures.



He - Water	Air - Water	Mix_2 - SPT	Mix_2 - Water	Mix_4 - Water
$DR = 0.0002$	$DR = 0.0012$	$DR = 0.0011$	$DR = 0.002$	$DR = 0.004$
(a)	(b)	(c)	(d)	(e)

Fig. 2 – Free surface of the breaking wave before impact with repeated motions and different gas-liquid density ratios at scale 1 : 20

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