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Sloshing in a closed domain under unidirectional excitation

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Sloshing is a phenomenon where a partially filled tank is exerted into various environmental sea conditions, such as wave and wind. Sloshing in a tank of liquefied natural gas carrier can lead to structural damage of tank structures and motion instability of the carrier. Thus, sloshing analysis needs to be conducted beforehand to minimize the risk of damages. This paper presents experimental and numerical study on sloshing phenomenon in a prismatic membrane tank model under unidirectional excitation with 30% water filling condition. A regular wave motion stimulated by the linear actuator was applied to the model tank and recorded by a video camera. Meanwhile, OpenFoam software was used to simulate the sloshing numerically in a volume of fluid method based on Navier-Stokes theorem. The sloshing patterns and free surface elevation in the prismatic membrane model tank, with the same input amplitude and frequency, were investigated for both cases. Both experimental and simulation results showed reasonable agreement on the sloshing profile, while the internal free surface elevation in the closed domain indicated a deviation with maximum absolute error of 4.9 cm.

[**Keywords**: Sloshing; LNG; OpenFOAM; Free surface; VoF]

Introduction

Sloshing is a phenomenon where liquid in a partially filled tank moves in back and forth motions inconsistently with respect to external excitation. Liquid sloshing in a moving tank poses major issues in various dynamic systems such as underwater vehicles[1–3], tankers, liquefied natural gas (LNG) carriers, floating structures[4], vessels with moonpool[5,6], and petroleum cylindrical tanks[7]. Sloshing of liquids in partially filled tanks also refers to the transfer of liquid from one side of the tank to the other in the form of a wave, excited by periodic motion of the tank, either angularly or in translation[8]. Abramson[9] attributed the nonlinear effects of sloshing in the tanks as due to its geometry, large and coupling and instabilities of various modes. Sloshing may lead to large stress onto the local structures and damage of the containment structure. Abramson[9] presented a study where all kinds of damages due to sloshing are described. Lee et al.[10] reported that partially filled tanks with fluids are prone to violent sloshing under certain dynamic conditions. For example, when the frequency of the tank motion is close to the natural frequency of the interaction between sloshing fluid and tank structure, the enhanced fluid motion in the tank creates localized high impact loads on the tank walls and ceiling, which can cause structural damage[11]. Sloshing in tanks also leads to various dynamic phenomena such as resonance and coupled motion. Significant sloshing may affect the motion and stability of the ship. The effects of liquid sloshing are expected to be large when the excitation frequencies of the ship are close to the natural sloshing frequencies. Thus, sloshing analysis needs to be performed beforehand to observe the sloshing flow and impact to avoid severe problems.

Various methods are used to study sloshing phenomenon, such as theoretical, experimental, and numerical methods. In the early days, Abramson[9] reviewed sloshing phenomenon, and later, Faltinsen[12] proposed a nonlinear analytic method using a perturbation theory which is basically applied to a potential flow. Theoretical method has limitation as liquid sloshing is highly nonlinear and has transient motions. Experimental studies have been the most common approach to study liquid sloshing phenomenon and impact pressure. Akyildiz and Unal[13], Rognebakke et al.[14] and Younes and Younes[15] studied sloshing phenomenon and measured impact pressure in partially filled rectangular tank. Nonetheless, experimental approach still faces a major challenge which is the difficulty in scaling the model sloshing loads[9].

The numerical method has become popular to study sloshing as it is able to solve highly nonlinear problems. There are various approaches of numerical simulation to study liquid sloshing such as boundary element integral methods, finite element methods (FEM) for potential flow, finite difference method (FDM), finite volume method, and smoothed particle hydrodynamics method (SPH). Kim et al.[16] used FDM to study violent sloshing flows and its impact focusing on the global flow and free surface profile. They concluded that sloshing flows in three-dimensional prismatic tanks can have higher velocities around the upper chamfer than in two-dimensional case[16]. Later, Kim et al.[17] developed a FEM code for investigating three-dimensional impact pressures at the tank corners based on velocity potential theory and Hamilton's principle. SPH was utilized by Delorme et al.[18] to simulate sloshing phenomenon, with highlights on the critical points. The results were acceptable in the order of magnitude and approximation in the sloshed surface profile[18]. This SPH method was also used by Rudman and Paul[19] to model sloshing in a two-dimensional water model. The free surface profiles were in reasonable qualitative agreement for many of the different sloshing cases. However, the presence of bubbles in the modeling was not parallel to experiments, which made comparison more difficult. Colagrossi et al.[20] conducted an experimental and numerical investigation of two-dimensional sloshing problems using SPH method. They observed that wave surface along the tank and the alternation of the breaking phenomenon at the two tank sides were asymmetrical when the period was near the linear sloshing natural period.

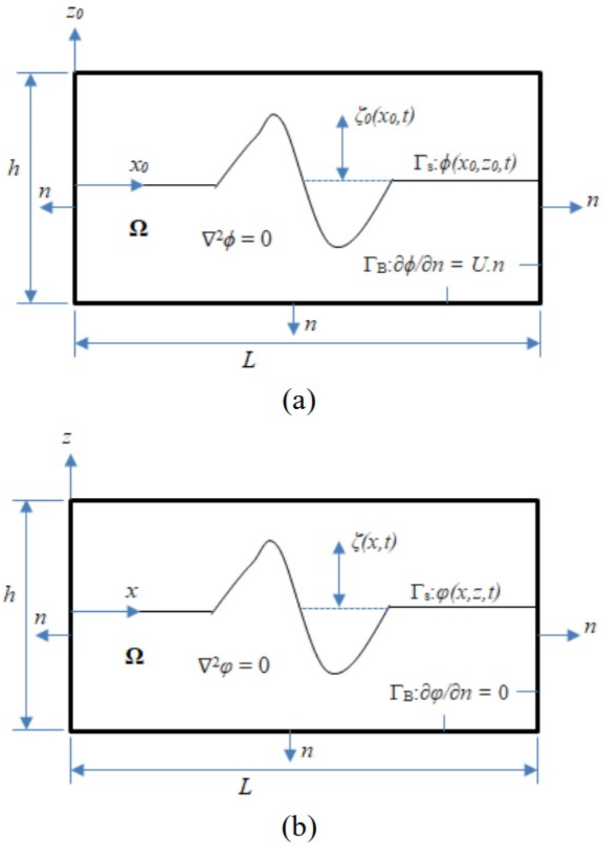
Volume of fluid (VoF) method developed by Hirt and Nicholas[21] is a renowned method to simulate the nonlinear flow. Djavareshkian[22] used VoF method for studying the internal liquid flow in truck containers and concluded that VoF can effectively solve the sloshing problem for different fluids and a variety of physical and geometrical conditions. Ha et al.[23], on the other hand, studied the nonlinear behavior of liquid sloshing using VoF by finite difference approximations with a moving coordinate system to find the sloshing loads and free surface profile. Akyildiz[24] compared the results of the sloshing phenomenon by experiment and numerical studies using rectangular tank. The sloshing phenomenon was simulated by employing VoF via computational fluid dynamics (CFD) to solve Reynolds Averaged Navier-Stokes Equations (RANS). Later, Rezaei and Ketabdari[25] developed a VoF based code, with the implementation of an additional transport equation, to calculate dynamic loads arising from sloshing in partially filled tanks. Huijsmans et al.[26] conducted numerical simulation based on the VoF method to observe the wave profile and its impact load on LNG tank hull in resonance condition. A finite volume discretization was used to discretize the Navier-Stokes equations in conservation form.

This paper presents investigation on sloshing phenomenon by using both experimental and numerical simulations. A tank with a filling volume of 30% was investigated under numerous regular motions at different amplitudes and period conditions. Sloshing in a closed domain (a prismatic model tank) was studied experimentally by capturing the free surface profiles using a video camera. The same sloshing condition was simulated by employing the VoF method for a multiphase case in OpenFOAM software. The sloshing motion and free surface profile from the numerical results were then compared to the experimental data. This study provides insightful relationships between unidirectional sloshing and water free surface elevation in a closed domain.

Methodology

To investigate the relationships between unidirectional sloshing and the water-free surface elevation in a closed domain, a numerical model of an enclosed water surface using VoF method was modeled and tested in an open source code, OpenFOAM. Later, the simulation results were validated with the experimental data.

The mathematical formulations of sloshing for a two-dimensional case excited by sway and heave motion were adopted from simplification by Sriram et al.[27]. Figure 1 shows a fixed coordinate system $o_o x_o z_o$ and a moving coordinate system *oxz* in a tank, in which these two systems coincide with each other when the tank is at rest.



(a)

(b)

Fig. 1 — Sloshing wave tank model in closed domain with (a) fixed coordinate system and (b) moving coordinate system[27]

The boundary conditions of the closed domain in each coordinate system are shown in Figs 1(a) and 1(b). In potential flow theory, the velocity potential, ϕ satisfies the Laplace equation in the fluid domain, Ω as[28]

$$\nabla^2\phi = 0 \qquad \dots (1)$$

The component of the water particle velocity normal to the side walls Γ_B of the tank is equal to the tank velocity in motion, as

$$\frac{\partial\phi}{\partial n} = U \cdot n \qquad \dots (2)$$

where n refers to outward normal vector and $U = dX_t/dt$ is velocity of the tank, X_t is displacement of the tank. The free surface motion can be described in the moving coordinate system as[27]

$$\frac{\partial\phi}{\partial t} - \nabla\phi \cdot \frac{dX_t}{dt} + \frac{1}{2}\nabla\phi \cdot \nabla\phi + g(\zeta) = 0 \qquad \dots (3)$$

where ζ is surface elevation from the initial still water height.

Numerical modeling

For numerical simulation, OpenFOAM software was utilized to compute the sloshing motion and free surface profile. To observe the liquid sloshing inside a prismatic membrane tank, VoF method was employed. This method was used to solve the incompressible Navier-Stokes (NS) equations with a free surface boundary condition, by reconstructing the free surface which separates the air and liquid in each computational cell making it suitable to predict all phases of the free surface problem. A two-dimensional multiphase *interDyMFoam* solver in OpenFOAM was used for handling the dynamic mesh. The governing equation of the fraction function C of fluid in a grid unit is defined as[21]

$$\frac{\partial C}{\partial t} + \nabla(Cu) = 0 \qquad \dots (4)$$

where C=1 refers to grid being fully occupied by fluid, and C=0 refers to grid unit which is fully occupied by air. Value $0 < C < 1$ indicates a partially filled condition of fluid. The transport equation of the VoF for an incompressible flow can be defined as

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = 0 \qquad \dots (5)$$

where t refers to time, and u and v are velocity components in the coordinate x- and y-direction, respectively. The continuity and momentum equation for a fluid motion with a free surface in a domain Ω is represented as

$$\left\{\begin{matrix} \rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u - f\right) - \nabla \cdot \sigma = 0 \\ \nabla \cdot u = 0 \end{matrix}\right\} \quad \text{in} \quad \Omega \qquad \dots (6)$$

where ρ is constant density of a liquid, f is volume force on the liquid, and σ is tensor of deformation rate.

Experimental set-up

A test rig of closed domain water surface elevation system was developed to determine the effects of increasing sloshing amplitude and frequency on the water surface profile. The system consisted of two main parts, which were a closed prismatic membrane model tank, and a direct current (DC) linear actuator, as illustrated in Fig. 2. The prismatic membrane tank model was made of the transparent acrylic plate by scale of 1:100 with uniform thickness of 5 mm (Fig. 3(a)). The principal dimensions of the tank model are shown in Figure 3(b). A camera was used to record the water surface profile at a frame rate of 30 frames per second (fps) with pixel resolution of 3840×2160. The camera was placed in front of the model tank to record the liquid sloshing motion in the tank; meaning the sloshing motion was recorded at one angle only, from the front panel. The video resolution was 1920×1080 at 401 pixels per inch; corresponding to 158 pixels per centimeter. The camera was placed at 60 cm perpendicular to the mid-point of the rail of the DC linear actuator. Water surface elevation at this position was of interest since the water breaking due to the change of linear drive actuation direction would be highly nonlinear. Filling ratio of water inside the tank was fixed at 30% of the tank volume because this amount of water is critical in sloshing due to the nonlinearity of sloshing flow, as wave breaking is more dominant under lower filling condition[28].

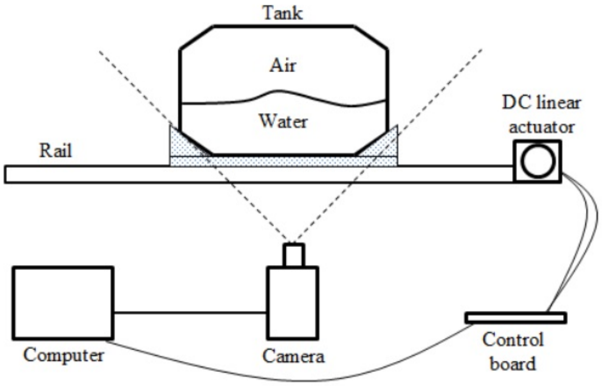
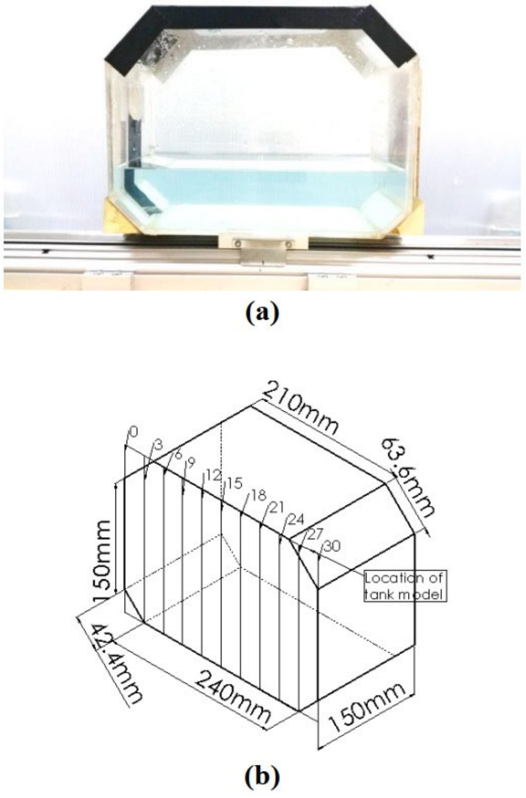


Fig. 2 — Test rig of closed domain water surface elevation system under unidirectional sloshing.


(a)

(b)

Fig. 3 — Model of prismatic membrane tank (a) front view and (b) principal dimensions and stations.

Image processing of videos of wave elevation inside the tank was conducted using *Digitize* software. Eleven snapshots at the same time interval were retrieved from a complete cycle of sloshing video clip of each test condition. Moreover, the tank model was divided into 11 stations along the length, as shown in Figure 3(b). The free surface elevation for each station was recorded; hence, a surface profile matrix of 11×11 was obtained for each test condition.

The linear actuator was uni-directionally actuated by a DC motor to closely follow a prescribed sloshing motion at different swaying amplitude and frequency. Figure 4 shows a prescribed linear actuator motion for amplitude A=2 cm and frequency F=2 Hz. To ensure that the linear actuator strictly followed the prescribed motions, a proportional and integral (PI) controller was applied through the use of an Arduino UNO board. Controller gains of K_p=150 and K_i=50 were heuristically fine-tuned to ensure the maximum absolute tracking error to always be less than 7.5%, equivalent to ±0.15 cm. The input data of frequency

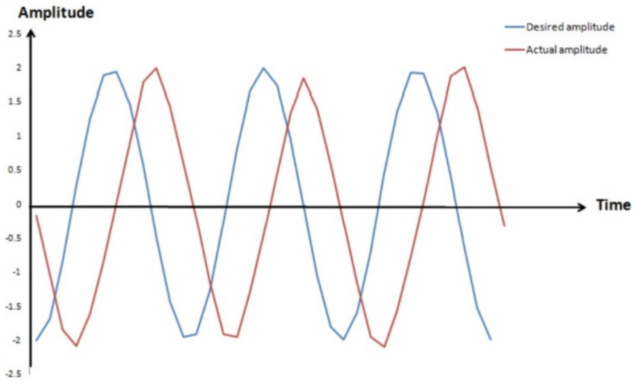


Fig. 4 — Example of linear drive actuator tracking of prescribed sloshing profile (amplitude=2 cm, frequency=2 Hz)

and amplitude were then scaled down based on 10 year return-period condition of South China Sea states[29], as listed in Table 1.

Table 1 — Regular wave input

Amplitude, *A* (cm)	Frequency, *F* (Hz)	
2.0	2.0	1.0
4.0	1.0	
6.0	1.0	
8.0	1.0	
10.0	1.0	

Results and Discussion

In this study, the artificial sloshing produced different water flow and wave elevation at different amplitudes and frequencies for both experimental and numerical analysis. Fig. 4 shows the results of sloshing profile and free surface elevation in a closed domain at different amplitudes and excitation frequencies. The simulation results of sloshing profile from Open FOAM generally agree with the experimental results for all cases. For case of amplitude *A*=2 cm (frequency *F*=2 Hz and *F*=1 Hz) as shown in Figures. 4(a)–4(b), the liquid free surface inside the tank remained relatively calm, and violent sloshing, such as splashing, was not observable in both experiment and simulation in these conditions. In the simulation results, the blue color refers to fluid fraction function *C*=1, whereas the white color refers to *C*=0. The intermediate layers indicate mixture of air/liquid where $0 < C < 1$.

Water splashing was noticeable along the side wall of the tank beginning from excitation amplitude *A*=4 cm and frequency *F*=1 Hz, as shown in Figure 5(c). The liquid flow inside the tank started to become highly nonlinear, and the flow elevated up to the upper chamfer (which was connected to the side wall) with a larger velocity of water particles when the excitation velocity of the tank was reduced suddenly from 4 cm/s to 0 cm/s during the changing state of moving direction, while the internal liquid still maintained high velocity. Amplitude *A*=6 cm and *A*=8 cm at frequency *F*=1 Hz (Figs 5(d)–5(e)) caused the sloshing to become further nonlinear. The liquid flow inside the tank became more violent and water splash hit the tank top in both cases. For instance, a particular case for snapshot T=0.09 s in Figure 5(e), the diverting flow after hitting tank top was captured in both experiment and simulation. Moreover, the free surface profile at T=0.63 sec in Figure 5(e) clearly indicates the simulation matches very well with the experiment at the same time series.

The sloshing motion became highly nonlinear as the excitation amplitude was set larger. In the case of sloshing motion at excitation amplitude *A*=10 cm and frequency *F*=1 Hz, the unidirectional velocity of the tank reached as high as 10 cm/s. Liquid flow inside the tank was violent as the water splash hit the tank top and was further diverted across the top plate. The momentum was large, as shown by the snapshots from T=0.45 s to T=0.63 s in Figure 5(f). Formation of bubbles was observed in the simulation, as shown in Figure 5(f) but this phenomenon was not obvious in the experiment. Therefore, a high-speed camera is needed in the future work.

When the sloshing became more violent, a higher error of the free surface elevation in between the experiment and simulation was noticeable. In this study, the most violent sloshing was observed at amplitude *A*=10 cm and frequency *F*=1.0 Hz (Fig. 5(f)). Meanwhile, the highest free surface elevation was nearly 20 cm, recorded at amplitude *A*=8 cm and frequency *F*=1.0 Hz, as shown in Figure 5(e). Wave breaking and splashes occurred as the excitation amplitude was set larger. According to the results, sloshing flow in our case due to 30% water filling condition had strongly nonlinear free surface flow and liquid run-up along the tank wall, together with water splash. Accurate prediction of such sloshed flow was an extremely difficult task to be fully solved computationally. As mentioned above, when the primary concern is to obtain accurate prediction of the sloshing flow instead of sloshing induced impact pressure, it is reasonable to apply the assumption that local flows play a significant role in the impact occurrence[28].

Note that the current study was restrained from the uni-directional simulation study. In real life situation, external excitation can be in a multi-dimension. Nonetheless, this study provides a significant insight of comparison of utilization of both experimental and simulation methods to predict sloshing flow and free surface elevation. In future works, a multi-dimensional excitation can be further investigated. Furthermore, the impact pressure exerted by sloshing on the tank wall can be determined. The method for simulation can be improved to track the free surface

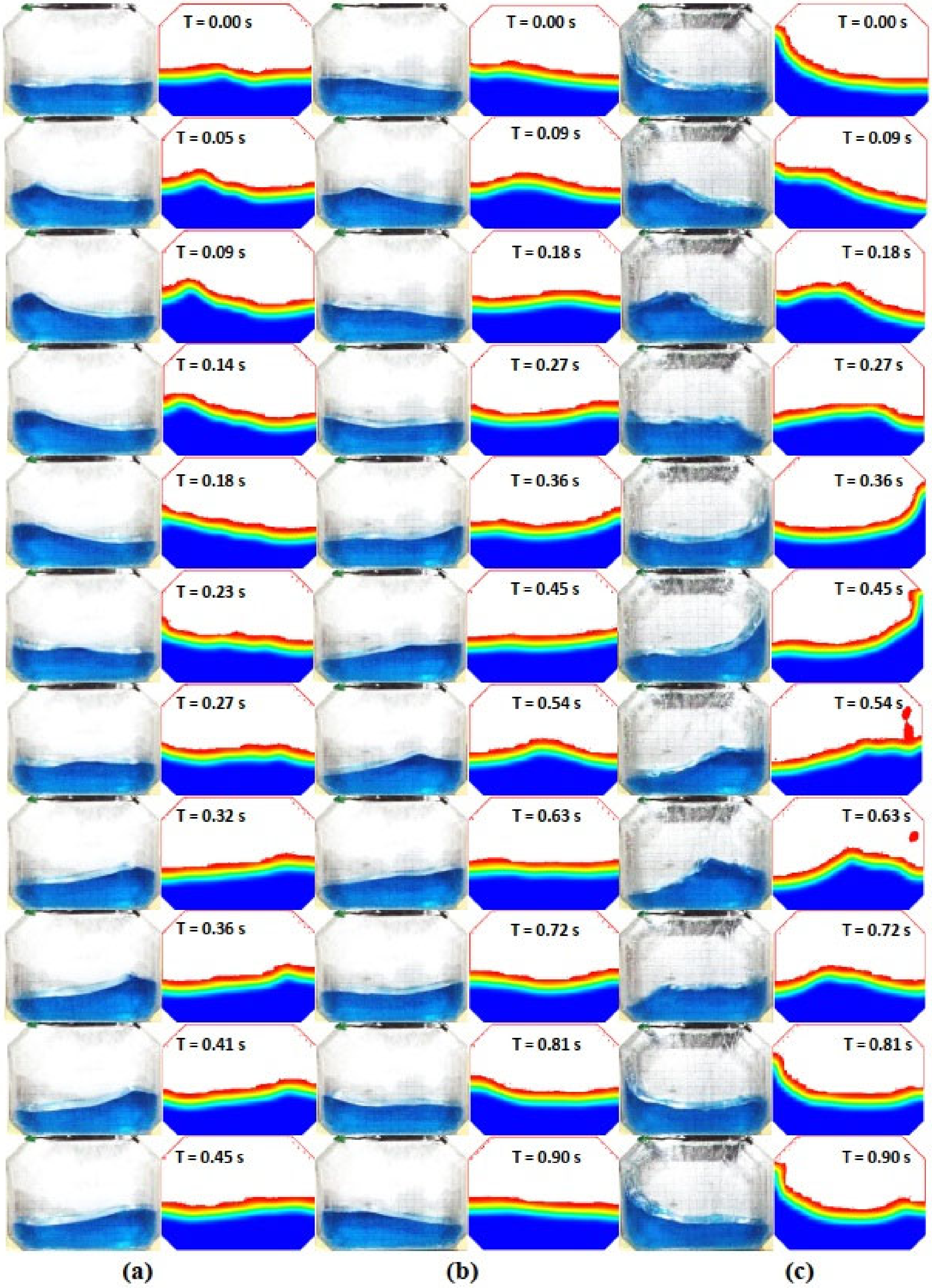


Fig. 5 — Comparison of sloshing wave flow from experiment and numerical studies for (a) A = 2 cm and F = 2 Hz, (b) A = 2 cm and F = 1 Hz, (c) A = 4 cm and F = 1 Hz, (d) A = 6 cm and F = 1 Hz, (e) A = 8 cm and F = 1 Hz, and (f) A = 10 cm and F = 1 Hz.

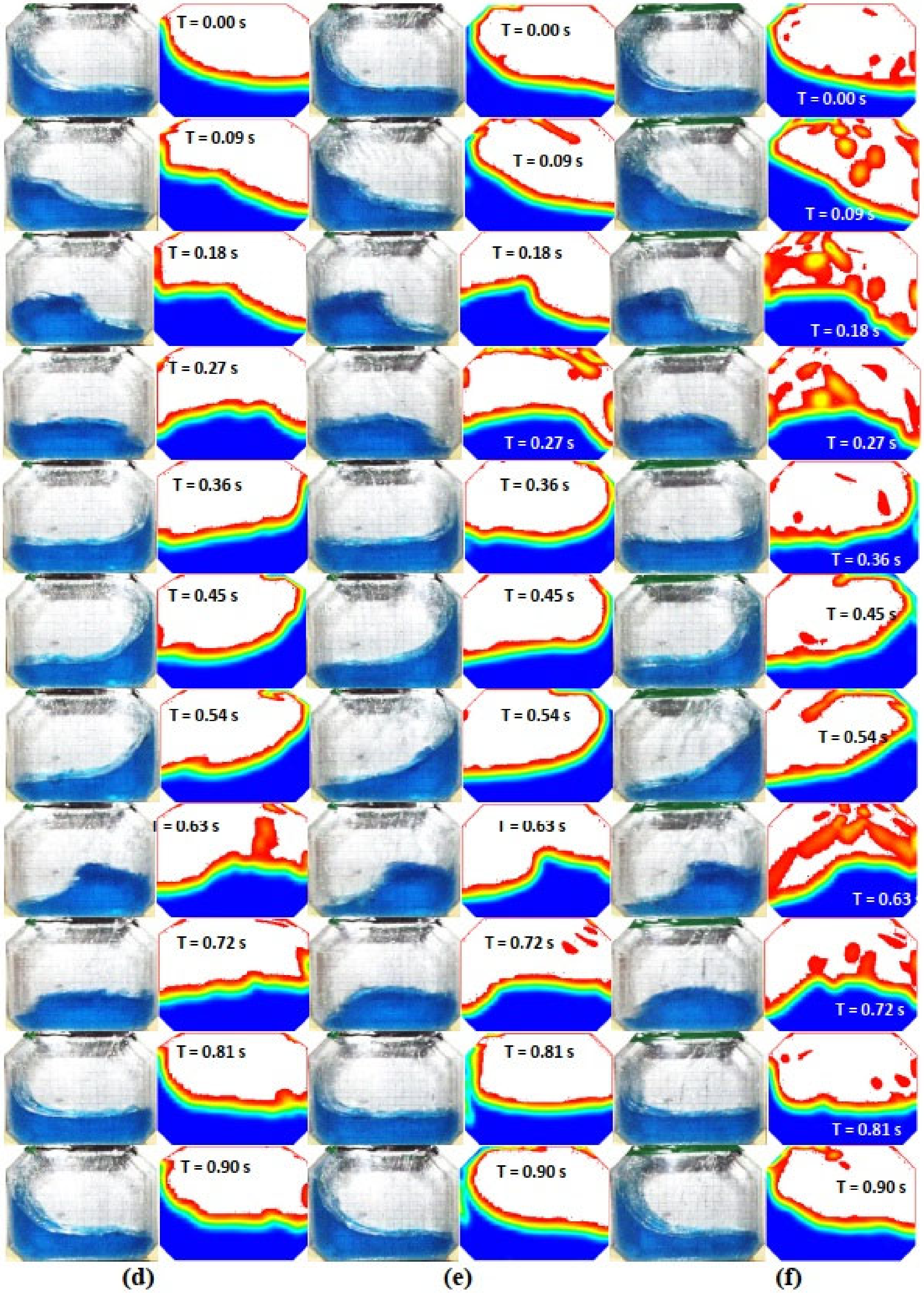


Fig. 5 — (*continuation*) - Comparison of sloshing wave flow from experiment and numerical studies for (a) A = 2 cm and F = 2 Hz, (b) A = 2 cm and F = 1 Hz, (c) A = 4 cm and F = 1 Hz, (d) A = 6 cm and F = 1 Hz, (e) A = 8 cm and F = 1 Hz, and (f) A = 10 cm and F = 1 Hz.

more accurately. Turbulent flow model using RANS to obtain deliberate time and spatial discretization can be considered[30] or using SST turbulence model to get a better accuracy of the sloshing flow[21].

Conclusion

Liquid sloshing in a closed domain investigated using a prismatic model tank with a scale of 1:100. A numerical simulation in Open FOAM based on the VoF method using *InterDyMFoam* solver was conducted to solve the multiphase case of sloshing. A tank with a filling ratio of 30% was excited in uni-directional motion set with an amplitude of 2, 4, 8, and 10 cm. The sloshing profile and free surface elevation became violent and highly nonlinear, as the excitation amplitude was set larger. The predictive results of sloshing flow using a two-dimensional model match well with the experimental results. A combined comparison of free surface elevation shows maximum difference of 4.9 cm. Hence, the experiment is important to obtain a sloshing profile for highly nonlinear condition.

To further understand sloshing behaviors, more experimental work and simulations are needed in future to create structural assessment of LNG membrane tank. Application of *k-ε* turbulence model and smaller mesh size may improve the simulation results. Highly sensitive pressure sensors are needed in future experimental work to measure sloshing impact forces. Understanding on sloshing can lead to development of anti-sloshing devices to ensure structural safety and integrity.

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