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Single-phase and Two-phase Smoothed Particle Hydrodynamics for Sloshing in the Low Filling Ratio of the Prismatic Tank

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ABSTRACT

The present study is to carry out a numerical sloshing using smoothed particle hydrodynamics (SPH) in the prismatic tank. Sloshing is a violent flow caused by the resonance of fluid in the tank by external oscillation. The prismatic tank was used to resemble a membrane LNG type carrier. The sloshing experiment was carried out using three pressure sensors, a camera high resolution, and four degrees of freedom forced oscillation machine. In this study, a filling ratio of 25% was used to reproduce sloshing in a low filling ratio. Only roll motion is used in the numerical simulation. Roll motion is directly imposing from the experiment displacement, and a comparison of hydrostatic and dynamic pressure was made to validate the SPH result. The time duration of the sloshing is the same as the experiment. Single-phase and multiphase SPH are conducted to reproduce sloshing in the prismatic tank. Sloshing was done both for the 2D and 3D domain. It shows that SPH has a good agreement with analytical and experimental results. The dynamic pressure is similar to an experiment through a spurious pressure oscillation exist. The dynamics pressure results show fairly for short time simulation and slightly decrease after that. The free surface deformation tendency is similar to experiment.

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NOMENCLATURE

F	Force	t	Time
P	Pressure	δ_{Φ}	Delta-SPH
r	Position vector	ρ	Density
m	Mass	v	Velocity
h	Smoothing length	w	interpolation kernel
α	Coefficient of artificial viscosity	γ	Adiabatic index

1. INTRODUCTION

The sloshing phenomenon is one of the challenging event in a liquid carrier such as an LNG ship, tanker, and oil truck carrier. Sloshing can define as a resonance of fluid inside a tank caused by an external oscillation. As sloshing dealing with nonlinear behavior, numerical and experiment method is the appropriate approach to tackle this problem. Many studies have been carried out to overcome sloshing using numerical method both of mesh CFD (computational fluid dynamics) and meshless CFD. Using an open-source CFD solver OpenFOAM [1] dynamic pressure was well-validated with the experimental result. Jiang et al. [2] did a numerical simulation of the coupling effect between ship motion and liquid sloshing under wave conditions. The results revealed that sloshing impact loading has no significant coupling effect on global ship response. Sanapala et al. [3] have used OpenFOAM to simulate parametric liquid sloshing with the baffled rectangular container to get optimal baffles. The results showed optimal baffles were obtained with reference to the quiescent free surface. Xu et al. [4] perform sloshing

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simulation using OpenFOAM to validate the OWC model. Xue et al. [5] used a different shape of tank to validate impact pressure distribution using OpenFOAM. Hu et al. [6] performed numerical sloshing using the boundary element method with different shapes of tanks. It showed that natural frequency has a relationship with the tank shape and empirical formulas were proposed by Hu et al. [6]. Sengupta et al. [7] have modeled a drying of MUGA silk using Fluent. It was showed mesh-based CFD has been used to overcome sloshing or real-life problems. It shows CFD as one of the prominent methods in numerical simulation. However, to deal with large deformation and violent flow mesh-based CFD needs special treatment to track free surface position; moreover, it will need a very fine mesh to get appropriate accuracy. In contrast, meshless CFD has the advantage to overcome large deformation and free surface deformation because of nature meshless and Lagrangian approach.

Smoothed particle hydrodynamics (SPH) is one of the meshless CFD methods developed for free surface flow by Monaghan [8]. Since then there is a lot of application of SPH for free surface flow for instance sloshing and water waves. Simulation of water waves has been sucessfully carried out in a large wave basin [9]. The result showed SPH had a good agreement with experiment. Using long-duration sloshing Green and Peiró has been successfully reproduced sloshing phenomena in low-fill and high stretching [10]. The hydrodynamics force and water height were well-captured compare to the analytic solution. However, there is no experimental data is used to verify or validate the results. This study was also carried out using a rectangular tank. Experimental validation has been conducted to reproduce violent sloshing using single-phase and two-phase SPH [11]. The results revealed that two-phase SPH had a better result than single-phase SPH in dynamic pressure and pressure evolution. In addition, to reduce pressure oscillation in dynamic pressure a low-pass filter technique is used [12]. A study was carried out using a large number of particles, more than 10 million. Gotoh et al. [13] performed a violent sloshing using an enhancement of Incompressible SPH in the rectangular tank. The result revealed higher order Laplacian SPH has a good agreement for pressure field. However, this study is presented in 2D with a rectangular tank. Two-phase SPH was carried out to simulate violent sloshing flows in a higher density ratio by Yun et al. [14] and it was revealed dynamics pressure has good accuracy with single-SPH and experiment results although the computation domain in 2D with a rectangular tank. Hashimoto et al. [15] performed numerical sloshing for oil storage using explicit moving particle simulation (MPS). This numerical computation was carried out using a large number of particles in a single phase. Dehghani and Shafiei [16] used SPH for cooling on the orthogonal cutting process of Ti-6Al-4V. It showed SPH can be used to simulate other fields that are related to real-life engineering problems. Simulation of water waves was carried out to validate SPH with experimental results done by Trimulyono and Hashimoto [17, 18]. In this study, SPH was used to reproduce of large deformation of water waves using an obstacle box. Besides, long-distance propagation is validated against experimental data. The results as predicted SPH has a good agreement with the experiment. Amanifarda et al. [19] used ISPH to simulate gravity waves in a short domain to reproduce water waves. Ghalandari et al. [20] did a numerical simulation of Squeezed Flow of a Viscoplastic Material. It shows SPH has a promising method to apply in complex and large deformation problems. Because of the merit of the meshless method that particle is carrying their own properties and solved using Lagrangian approach.

In the present study, multiphase sloshing simulation is carried out using open source SPH solver DualSPHysics ver 4.2 [21]. DualSPHysics has implemented general computing on graphics processing units (GPGPU) technology makes computation faster and reliable to simulate a large number of particles. Multiphase DualSPHysics has been developed for liquid and gases by Mokos et al. [22] with benchmarking cases for sloshing flow and dam break. The study itself carried out using the 2D domain. The sloshing simulation was carried out using the same condition with sloshing experiment duration time. The low filling ratio was used i.e. 25% filling ratio with one pressure sensor is used to validate dynamic pressure. The comparison of free surface deformation has made using single- and two-phase SPH. In addition, numerical computation of 3D two-phase SPH is carried out to take into account of air-phase in sloshing. Finally, a comparison is made both single- and two-phase with experiment results. It was found that SPH has acceptable results for both single- and two-phase. Free surface deformation is fairly reproduced by SPH both single- and two-phase SPH.

2. MATERIALS AND METHODS

2. 1. Smoothed Particle Hydrodynamics (SPH)

Sloshing is one of the challenging events in liquid carriers especially for large vehicles such as ships or airplanes. Because sloshing is dealing with large deformations of fluid inside the tank, meshless CFD has merit to apply to this problem. One of the meshless CFD is smoothed particle hydrodynamics that was developed by Monaghan for free surface flows [8]. SPH is a pure Lagrangian method that is based on integral interpolants that describe in detail in references [23]. SPH uses an interpolation approach to estimate fluid physical properties value and derivatives of a continuous field using discrete evaluation point/ particle. If there is a function of *F(r)* in the domain *(Ω)* to evaluate the contribution of the neighbouring particle using a kernel function (*W*) and smoothing length (*h*). Smoothing length is a characteristic length used to define the area of influence of the kernel. The integral approximation shows by Equation (1) and the particle approximation shows in Equation (2) at a particle *a* where is *m* is a mass, ρ is density and *r* is position.

$$F(r) = \int_{\Omega} F(r) W(r - r', h)\, dr \tag{1}$$

$$F(r_a) \approx \sum_b F(r_b) W(r_a - r_b, h) \frac{m_b}{\rho_b} \tag{2}$$

Equation (3) shows a continuity equation with delta-SPH to suppress density fluctuation. where δ_{Φ} is delta-SPH. Equation (4) is a momentum equation in the Lagrangian form in SPH. Π_{ab} is artificial viscosity term based on Monaghan's work and *v* is velocity. *r* is the distance between two particles. Equations (5) and (6) are the equation of state in the SPH form for water, and air, respectively. γ is polytropic constant and c_0 is the speed of sound at reference density. where $a = 1.5g\left(\frac{\rho_w}{\rho_a}\right)L$ with ρ_w, ρ_a, L, and X are initial water density, air density, characteristic length of the domain, and the constant background pressure. The time step is calculated base on the works of Monaghan et al. [24].

The experiment condition was based on the work of Trimulyono et al. [11]. In this study, only a low filling ratio with violent motion was used. The pressure sensor was set in the near-free surface for the detailed information reported in literature [11].

$$\frac{d\rho_a}{dt} = \sum_b m_b v_{ab} \cdot \nabla_a W_{ab} + 2\delta_{\Phi} h c_0 \sum_b (\rho_{b} - \rho_a) \frac{r_{ab} \cdot \nabla_a W_{ab}}{r_{ab}^2} \frac{m_b}{\rho_b} \tag{3}$$

$$\frac{dv_a}{dt} = -\sum_b m_b \left(\frac{P_{a+P_b}}{\rho_a \cdot \rho_b} + \Pi_{ab} \right) \nabla_a W_{ab} - 2a\rho_a^2 \sum_b \frac{m_b}{\rho_b} \nabla_a W_{ab} \tag{4}$$

$$where\ \Pi_{ab} = \begin{cases} \dfrac{-\alpha \overline{c_{ab}} \mu_{ab}}{\overline{\rho_{ab}}} & v_{ab} \cdot r_{ab} < 0 \\ 0 & v_{ab} \cdot r_{ab} > 0 \end{cases}$$

$$P = \frac{c_0^2 \rho_0}{\gamma} \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right] \tag{5}$$

$$P = \frac{c_0^2 \rho_0}{\gamma} \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right] + X - a\rho^2 \tag{6}$$

$$\Delta t_{cv} = \min \frac{h}{c_s + max \left| \frac{h v_{ab} \overset{a}{\cdot} r_{ab}}{\left(r_{ab}^2 + \eta^2 \right)} \right|} \tag{7}$$

Figure 1 depicts the prismatic tank that was used in the experiment. It shows pressure sensor location is at a free surface in rest condition. The filling ratio is 25 %, where this condition is very risky for the filling ratio of the tank, especially for a ship in roll motion.

3. RESULTS AND DISCUSSION

Sloshing simulation in the prismatic tank has conducted in two- and three-dimensional, firstly two-dimension numerical simulation conducted. Two-phase SPH is more reliable executed in the two-dimensional domain because the speed of sound is larger in two-phase SPH as a result of the speed of sound in the air. As a consequence time-step in two-phase SPH more small as defined in Equation (7). This makes computation in two-phase SPH very high compare to using single-phase. However, in the reality almost free surface flow is two-phase SPH or multiphase. In this study, 3D sloshing of two-phase SPH was carried out to reproduce sloshing in a low filling ratio.

Table 1 shows parameters setup for two-phase SPH both for 2D and 3D. Some parameter is changed in 3D domain because to compromise computational cost that increases caused by two-phase SPH in 3D. It can be explained that computation increase drastically by interpolation of neighbouring particle and speed of sound in the air phase. It can be caused by the speed of sound are directly using real numbers but it will increase computation time as expressed in Equation (7). To get appropriate accuracy and reliable computation time, selected speed of sound chosen based on the 2D result. Another reason is interpolation for the neighbour particle in the 3D domain higher to take into account air-phase particle. The total particle for the 2D domain is less than 100.000 and more than 1 million for 3D. Computation time for two-phase SPH in 3D approximately 2 months only for 72 seconds using GPU GTX GeForce 1080 ti. On the contrary for single-phase, computation time only needs 2 days. It showed computation SPH for two-phase flow still high, not preferable for a large domain, but this obstacle will vanish when a multi-GPU code of DualSPHysics is released [25]. Coefh is the coefficient of smoothing

Figure 1. Prismatic tank with 25% filling ratio [11]

length, a different magnitude is used between 2D and 3D because time computation in 2D is less compare in 3D. Other parameters such as CFL was used in different number because the effect of computation time in 3D is very high. Because this reason some parameters are not yet optimized for the 3D domain. For the 3D domain, the initial particle distance change three times from the 2D domain, because the total particle will be more than 10 million using the same particle distance. Furthermore, the effect of speed of sound makes computation time larger than using single-phase SPH.

Hydrostatic pressure illustrated in Figure 2 showed hydrostatic pressure is well predicted by SPH. The accuracy of static pressure depicts from the color gradient which is a red color for high pressure located in the bottom of the tank both for single-phase and two-phase SPH. The pressure at the bottom showed 500 Pa, moreover, the difference from the analytic solution is below 3% compared with the analytical solution. The same results reported by Trimulyono et al. [11].

Figure 3 shows the comparison of dynamic pressure between single-phase SPH with the experiment in the two-dimensional domain. In this study, the movement of the tank is the same as the experiment condition. Simulation time is set for 72 seconds. Three timing time of simulation is used to show beginning, mid and edge of simulation. Figure 3 shows that there is no phase between SPH with experiment. It describes the velocity of water as the same both in SPH and experiment. As a result, the timing of the pressure sensor in SPH and the experiment is the same at time pressure sensor capture dynamic pressure. The red line is SPH and the purple line is the experiment result. The single-phase SPH showed the tendency of dynamic pressure is similar but the accuracy is slightly reduced after duration reaches 55 seconds in the simulation. The toe of dynamics pressure is not reproduced by single-phase SPH, the graph is flat in SPH but in the experiment, it has a toe. It can be explained that air-phase has an effect to dynamic pressure after run up and water is moved to the opposite wall. This result also consistent to the end of the simulation. The pressure fluctuation is very high in time simulation 55 to 65 seconds because of density fluctuation. this is the nature of weakly compressible SPH (WCSPH) because the equation of state is very stiff, although delta-SPH has been applied; however, it's only reduced density fluctuation. Incompressible SPH (ISPH) is one remedy of this problem that solved the equation of state using pressure poission equation (PPE), as result computation time increased. DualSPHysics was implemented ISPH, but not yet released as an open-source package in an online version.

Figure 4 shows the dynamic pressure between two-phase SPH with experiment results for the two-dimensional domain. Two-phase SPH shows a similar result with single-phase SPH; however, the accuracy is

TABEL 1. Parameter setup in numerical simulation

Parameters	**2D**	**3D**
Kernel function	Wendland	Wendland
Time step algorithm	Sympletic	Sympletic
Artificial viscosity coeff. α	0.07	0.07
Speed of sound (water & air)	65 & 478	46 & 200
Particle spacing (mm)	0.8	2.4
Coefh	0.95	1.2
CFL number	0.2	0.3
Delta-SPH (δ_φ)	0.1	0.1
Simulation time (s)	72.0	72.0

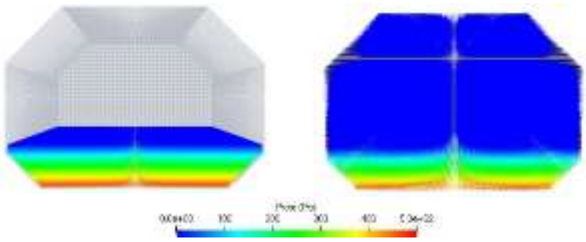


Figure 2. Hydrostatic Pressure in 3D domain

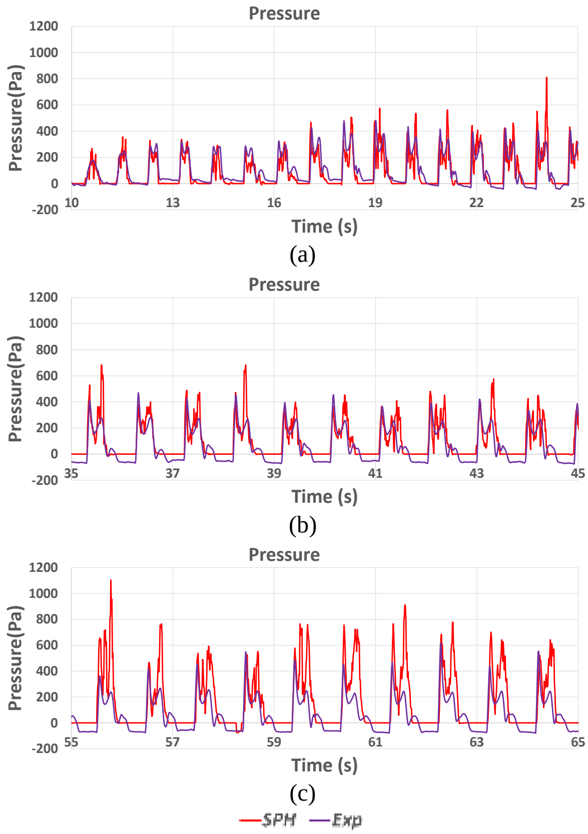


Figure 3. Comparison of dynamics pressure for single-phase SPH in (a) 15-25 s, (b) 35-45 s, (c) 55-65 s

much better to compare with single-phase. The toe of dynamic pressure in the experiment has successfully reproduced using two-phase SPH. It was found that air-phase has influence on dynamic pressure, as result, the toe in dynamic pressure was captured. The accuracy of two-phase SPH in the time simulation 55 to 65 seconds is better compare to single-phase SPH. The pressure noise is less than single-phase SPH. It depicts that air-phase has a significant effect in the sloshing phenomenon, moreover particle resolution is another parameter that needs to pay attention to as in the 3D domain it will be difficult to use high resolution for two-phase SPH.

Figure 5 shows the free surface deformation of water inside the tank. One of the merits of using SPH is mesh-free as a result, large deformation of fluid is easily captured by SPH as the nature of SPH does not need a special algorithm to capture the free surface position. This makes SPH suitable for violent flow such as sloshing. Figure 5 reveals two-phase SPH has good agreement with the experiment as in the single-phase SPH the fluid particle easy to detach from the boundary particle. It shows in run-up condition in single-phase SPH

Figure 6 shows a comparison of dynamic pressure single-phase SPH in the 3D domain. It shows the accuracy slightly decrease in simulation time 55 to 65 second. It can be caused by resolution was changed compare to 2D cases. The same phenomena as seen in the 2D domain. The toe of dynamic pressure could not capture by single-phase SPH, the same results as single-phase SPH in 2D simulation. Figure 8 depicts two-phase SPH in 3D. It showed two-phase SPH in the 3D domain is more complicated to handle as the time-step is larger and higher computation time. As result, dynamic pressure only reliable for short time simulation, after 35 seconds dynamic pressure showed pressure noise more dominant though in this study delta-SPH was used. The same result was achieved that is two-phase SPH could capture pressure toe as shown in Figure 4. Comparison

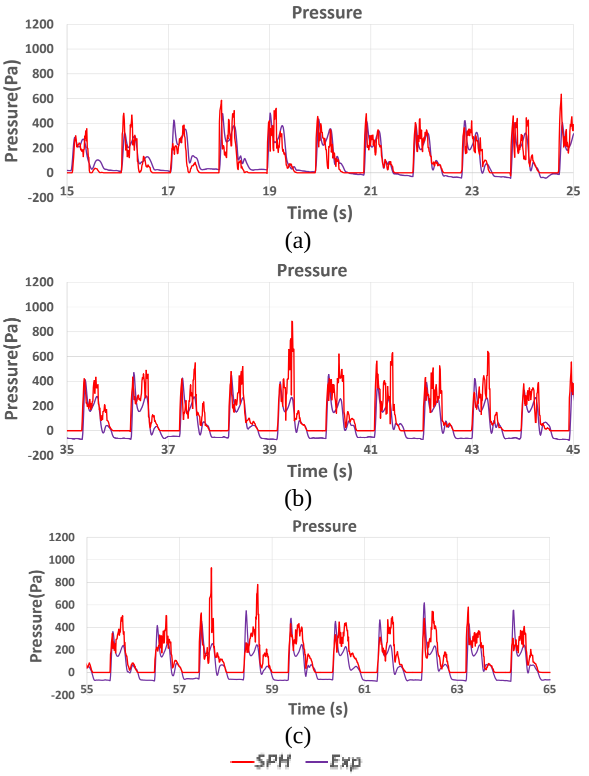


Figure 4. Comparison of dynamics pressure for two-phase SPH in (a) 15-25 s, (b) 35-45 s, (c) 55-65 s

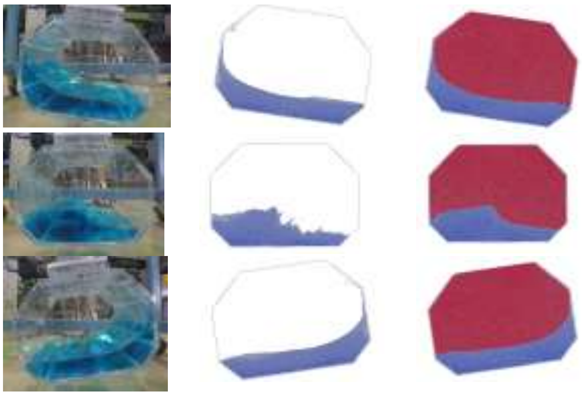


Figure 5. Comparison of free surface evolution in the 2D domain for SPH and experiment.

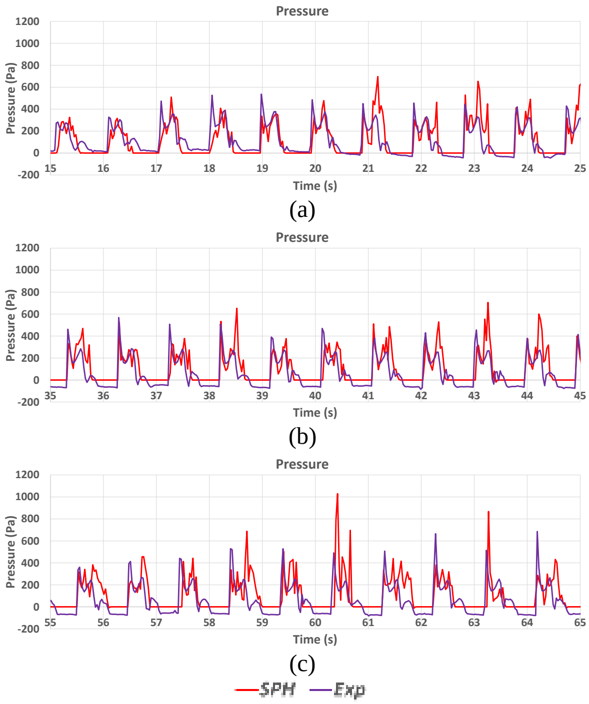
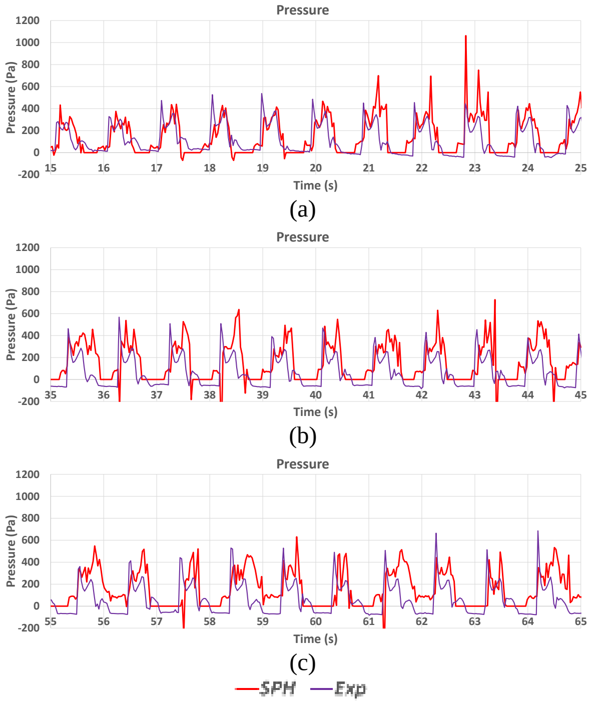


Figure 6. Comparison of dynamics pressure for single-phase SPH in 3D at (a) 15-25 s, (b) 35-45 s, (c) 55-65 s

of free surface deformation of water shown in Figure 8. It showed a smooth free surface deformation produced by single-phase SPH which is a bit different in 2D simulation. It can be caused by the 2D domain particle spacing is more dense compare to the 3D domain. Free surface deformation of water in two-phase SPH seen as there is an air-phase inside the tank cover up water particle that is some detail, the run-up in the tank was not clearly shown. However, a similar phenomenon was captured by SPH.



(a)

(b)

(c)

Figure 7. Comparison of dynamics pressure for two-phase SPH in 3D at (a) 15-25 s, (b) 35-45 s, (c) 55-65 s

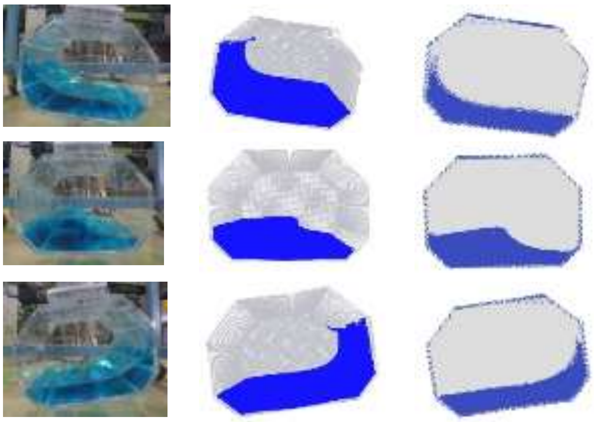


Figure 8. Comparison of free surface evolution between experiment and SPH

4. CONCLUSION

Single-phase and two-phase SPH of sloshing in the prismatic tank was successfully carried out in this study. The hydrostatic pressure has a good agreement with the analytical solution both for the 2D and 3D computation. It was shown that SPH has reasonably reproduced the dynamic pressure in the low filling ratio tank. Although in single-phase SPH, the toe of dynamic pressure cannot capture by SPH; however, multiphase SPH has successfully reproduced this phenomenon. It was revealed that air-phase has a significant effect on the sloshing phenomenon. Furthermore, Three-dimension SPH was carried out to reproduce the sloshing phenomena. It shows two-phase SPH reasonably reproduces dynamics pressure compared to single-phase SPH in short duration time simulation, and pressure fluctuations become dominant for long-duration simulation time. Free surface deformation is well captured by SPH, both single-phase or two-phase SPH. Moreover, two-phase SPH has a good agreement with the experiment result for 2D simulation because of a high-resolution particle spacing. The same results are shown by multiphase SPH, but accuracy slightly decreased for dynamic pressure. It was found to reproduce air entrapment in SPH needs a high-resolution particle spacing. Multiphase SPH in 3D is highly computational cost and accuracy tendency similar in the 2D domain for regular motion, as results for large domain computation multiphase SPH are not feasible. Sensitive parameters for sloshing in multiphase are needed to carry out future works, especially for the 3D domain. Future works such as the effect of baffle in the prismatic tank can be a candidate to reduce impact pressure in this study.

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Persian Abstract

چکیده

مقاله حاضر انجام یک برش عددی با استفاده از هیدرودینامیک ذرات صاف (SPH) در مخزن منشوری است. اسلشینگ یک جریان شدید است که در اثر تشدید مایع در مخزن در اثر نوسان خارجی ایجاد می شود. مخزن منشوری برای شبیه سازی یک حامل نوع LNG غشایی استفاده شد. آزمایش برش با استفاده از سه سنسور فشار ، یک دوربین با وضوح بالا و چهار درجه دستگاه آزادی نوسان مجبور انجام شد. در این مطالعه ، از نسبت پر شدن ۲۵٪ برای تولید مثل شلختگی در نسبت پرکردن کم استفاده شد. فقط حرکت رول در شبیه سازی عددی استفاده می شود. حرکت رول مستقیماً از جابجایی آزمایش تحمیل می کند و مقایسه فشار هیدرواستاتیک و دینامیکی برای تأیید نتیجه SPH انجام شده است. مدت زمان شلیک کردن همان آزمایش است. تک فاز و چند فاز SPH برای تولید مثل شل شدن در مخزن منشوری انجام می شود. Sloshing هر دو برای دامنه D۲ و D۳ انجام شد. این نشان می دهد که SPH توافق خوبی با نتایج تحلیلی و تجربی دارد. فشار دینامیکی مشابه آزمایش از طریق نوسان فشار جعلی است. نتایج فشار دینامیکی نسبتاً برای شبیه سازی کوتاه مدت نشان داده می شود و پس از آن اندکی کاهش می یابد. گرایش تغییر شکل سطح آزاد مشابه آزمایش است.