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The effects of T type baffle on liquid sloshing by MPS method

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Abstract

In this paper, an in-house mesh-free particle solver MLParticle-SJTU, which is developed based on improved moving particle semi-implicit (MPS) method, is employed to numerically simulate the effects of T type baffle on liquid sloshing under surge excitation. At first, a rectangular tank without baffles is modeled to simulate three-dimensional (3-D) liquid sloshing under surge excitation. And the MLParticle-SJTU solver can capture the complex flow phenomena, such as overturning of free surface, breaking wave, impacting the roof of the tank and so on. Secondly, liquid sloshing in same rectangular tank with two kinds of vertical baffles is modeled. The impact pressure and the deformation of free surface can be investigated clearly, indicating that the vertical baffles can reduce the impulse pressure. In order to reduce the pressure amplitude and violent sloshing further, the rectangular tanks with two different T type baffles are simulated numerically. Comparing to the results of the tank with vertical baffles, the T type baffles are more effective on reducing violent liquid sloshing because of the existence of horizontal baffle.

Keywords: Liquid sloshing; MPS; Vertical baffles; T type baffles

1 Introduction

Liquid sloshing is a common phenomenon in a partially filled container under external excitations, such as: liquid oscillations in fixed storage tanks caused by earthquakes, tank trucks over the rough road, sloshing of liquid cargo in vessels and the motion of liquid fuel in aircraft and spacecraft. The liquid flow of sloshing is complex and nonlinear. Even though the amplitude of external excitation is small, the sloshing will be violent and prone to occur local slamming. In the field of ocean engineering, liquid sloshing is still an important issue in LNG, LPG and FPSO which transport liquefied gas. Liquid sloshing is inevitable and dangerous under the harsh marine environment, especially the frequency of excitation near resonant frequency. The movement of liquid in tanks is drastic and the impact pressure of sloshing will destroy the structure of tank and intensify the motion of vessel. So, many researchers have devoted themselves to investigate the problems of liquid sloshing.

After the 1970s, a large amount of studies on liquid sloshing was carried out. At the early stage, the problem of two-dimensional (2-D) liquid sloshing was analyzed. Some representative studies were conducted by Faltinsen [1], Nakayama and Washizu [2][3]. Many theories and methods have been adopted to research this issue, such as a coupled BEM-FEM (Koh et al. [4]), the fully non-linear wave theory (Wang and Khoo [5]), the smoothed particle hydrodynamics (SPH) method (Shao et al. [6]) and so on. With the increase of knowledge and the improvement of computer power, researchers started to study 3-D liquid sloshing. A mountain of work has been conducted by Kim [7], Liu and Lin [8], Wu and Chen [9], Wu et al. [10], Lee et al. [11] and so on.

After predicting the influence of liquid sloshing accurately, researchers began focusing on the means of reducing sloshing amplitude. Setting up internal baffles is a simple and effective method. Kim [12] studied the 2-D and 3-D sloshing in a rectangular tank with a large vertical baffle and three horizontal baffles by using a finite difference method in 2001. In 2003, Gedikli and Ergüven [13] used variational BEM to study the effect of a rigid baffle on the natural frequencies of liquid in a cylindrical tank. Cho and Lee (2004) [14] and Cho et al. (2005) [15] investigated the effect of the baffle heights and opening widths on the large amplitude liquid sloshing in 2-D rectangular tank under horizontal external excitation. The 2-D sloshing in both rectangular and cylindrical tank with rigid baffles was investigated by using FEM (Biswal et al., 2006 [16]). In 2009, Panigrahy et al. [17] investigated the pressure variation on the walls and the surface elevation of liquid sloshing in a rectangular tank with ring baffles. In the same year, a numerical model has been developed by Liu and Lin [18] to study 3-D liquid sloshing in a tank with a horizontal baffle and a vertical baffle, respectively. Xue and Lin [19] modeled a 3-D numerical tank with ring baffle and investigated the effect of different ring baffle arrangements on sloshing in 2011. Multi-baffled containers with arbitrary geometries were modeled and the effect of size and position of baffle was surveyed by Ebrahimian et al. [20] in 2014. In 2015, Tang et al. [21] adopted the MPS method to research the effect of baffle height on sloshing in 2-D rectangular tank. Wang et al. [22] studied effects of T-shaped baffled parameters upon sloshing characteristics in a 2-D elliptical tank by using a semi-analytical scaled boundary finite-element method (SBFEM) this year.

In order to investigate liquid sloshing, we employ the MLParticle-SJTU solver based on improved MPS method to simulate 3-D liquid sloshing numerically in this paper. Some mathematical models of MPS are briefly introduced in first section. In the following section, liquid sloshing in a rectangular tank without baffles (CASE 1) is simulated under surge excitation. And the MLParticle-SJTU solver can simulate the complex flow phenomena, such as overturning of free surface, breaking wave, impacting the roof of the tank. Then, liquid sloshing in same rectangular tank with two kinds of vertical baffles installed in the middle of the bottom is modeled. The height of one baffle is 0.1 m (CASE 2) and another one is 0.15 m (CASE 3). The impact pressure and the deformation of free surface can be investigated clearly, indicating that the vertical baffle can reduce the impulse pressure. The pressure peak of CASE 3 is smaller in comparison to CASE 2. In order to reduce the pressure amplitude and violent sloshing further, the rectangular tanks with two different T type baffles are simulated numerically. A 0.2 m long horizontal baffle is placed on the top of vertical baffle (CASE 4 and CASE 5) based on CASE 2 and CASE 3, respectively. Comparing to the results of the tank with vertical baffle, the T type baffles is more effective on reducing violent liquid sloshing because of the existence of horizontal baffle.

2 Mathematical Formulation

The moving particle semi-implicit method (MPS) is a mesh-free method based on Lagrangian particle method. In essence, the flow field is presented by particles that contain the information of mass, velocity and so on. Because of this character, MPS method can simulate flow with large deformation and nonlinear fragmentation of free surface effectively. Koshizuka and Oka [23] have introduced the MPS method in 1996. And MPS method was modified by many other researchers in the following study (Tanaka and Masunaga [24], Lee et al. [25], Zhang and Wan [26]). In this section, only a brief introduction of MPS method is provided. There are several numerical models in MPS. They can be described as:

Governing Equations:

$$\frac{1}{\rho}\frac{D\rho}{Dt} = \nabla\cdot V = 0 \tag{1}$$

$$\frac{DV}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2 V + g \tag{2}$$

where ρ is the fluid density, t is the time, V is the velocity vector, P is the pressure, ν is the kinematic viscosity and g is the gravitational acceleration vector.

Kernel Function:

$$W(r) = \begin{cases} \dfrac{r_e}{0.85r + 0.15r_e} - 1 & 0 \le r < r_e \\ 0 & r_e \le r \end{cases} \tag{3}$$

where r is the distance between two particles and r_e is the radius of the particle interaction.

Gradient Model:

$$<\nabla P>_i = \frac{D}{n^0}\sum_{j\neq i}\frac{P_j + P_i}{|\boldsymbol{r}_j - \boldsymbol{r}_i|^2}(\boldsymbol{r}_j - \boldsymbol{r}_i)\cdot W(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \tag{4}$$

where D is the number of space dimension, n^0 is the initial particle number density and r is coordinate vector of fluid particle.

Laplacian Model:

$$<\nabla^2\phi>_i = \frac{2D}{n^0\lambda}\sum_{j\neq i}(\phi_j - \phi_i)\cdot W(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \tag{5}$$

$$\lambda = \frac{\sum_{j\neq i} W(|\boldsymbol{r}_j - \boldsymbol{r}_i|)\cdot|\boldsymbol{r}_j - \boldsymbol{r}_i|^2}{\sum_{j\neq i} W(|\boldsymbol{r}_j - \boldsymbol{r}_i|)} \tag{6}$$

where ϕ is an arbitrary scalar function and λ is applied to make sure that the increase of variance is equal to the analytical solution.

Model of Incompressibility:

$$<\nabla^2 P^{k+1}>_i = (1-\gamma)\frac{\rho}{\Delta t}\nabla\cdot V_i^* - \gamma\frac{\rho}{\Delta t^2}\frac{<n^*>_i - n^0}{n^0} \tag{7}$$

where γ is a blending parameter which varies from 0 to 1, n^* is the temporal particle number density and Δt is the time step. In this paper, $\gamma = 0.01$ is employed for all numerical simulations.

Free Surface Detection,

$$<\boldsymbol{F}>_i = \frac{D}{n^0}\sum_{j\neq i}\frac{1}{|\boldsymbol{r}_i - \boldsymbol{r}_j|}(\boldsymbol{r}_i - \boldsymbol{r}_j)W(\boldsymbol{r}_{ij}) \tag{8}$$

$$<|\boldsymbol{F}|>_i \;>\; \alpha \tag{9}$$

$$\alpha = 0.9|F|^0 \tag{10}$$

where F is a vector which represents the asymmetry of arrangements of neighbor particles, $|F|^0$ is the initial value of $|F|$.

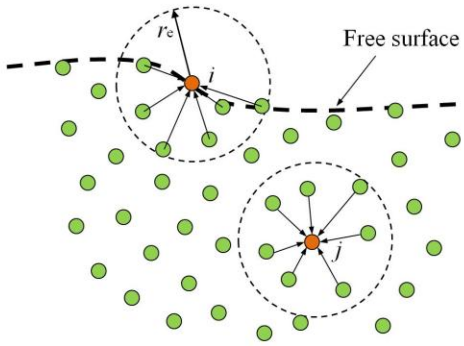

Fig. 1 Description of particle interaction domain

3 Results and Discussion

3.1 Numerical Models

In this section, a 3-D liquid tank is simulated numerically, which is same as the experimental model given by Kang and Lee (2005) [27] without baffles (CASE 1). The tank is 0.8 m long, 0.35 m wide, and 0.5 m high. The filling level is 50%, corresponding depth of water is 0.25 m. Based on CASE 1, two different vertical baffles are installed in the middle of the bottom. The heights of vertical baffles are 0.1 m (CASE 2) and 0.15 m (CASE 3), respectively. And two kinds of T type baffles (CASE 4 and CASE 5) are further modeled on the basis of CASE 2-3. Figs. 2-6 show the sketches of these five models. And the parameters of five cases are listed in Table 1.

Table 1 Parameters of five cases

	Vertical baffle	Horizontal baffle
CASE 1	-	-
CASE 2	0.1m	-
CASE 3	0.15m	-
CASE 4	0.1m	0.2m
CASE 5	0.15m	0.2m

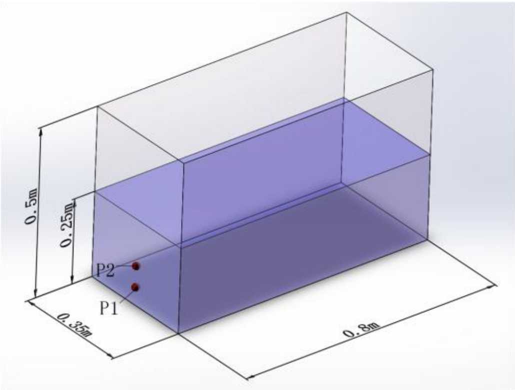

Fig. 2 The 3-D sketch of CASE 1

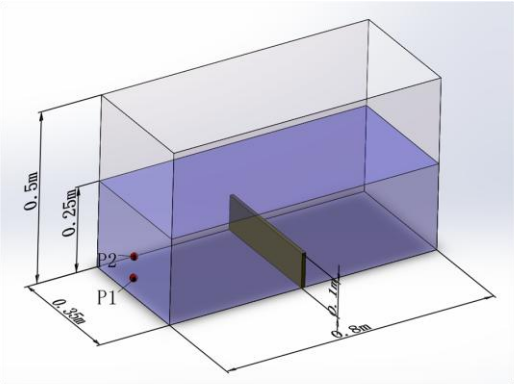

Fig. 3 The 3-D sketch of CASE 2

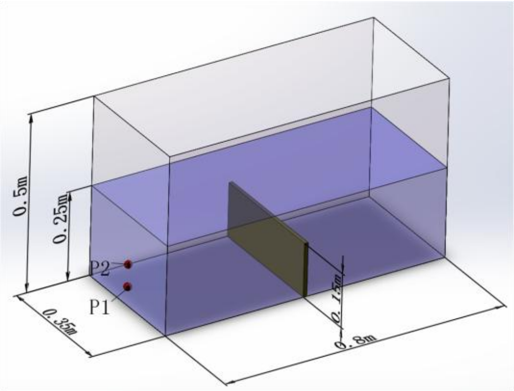

Fig. 4 The 3-D sketch of CASE 3

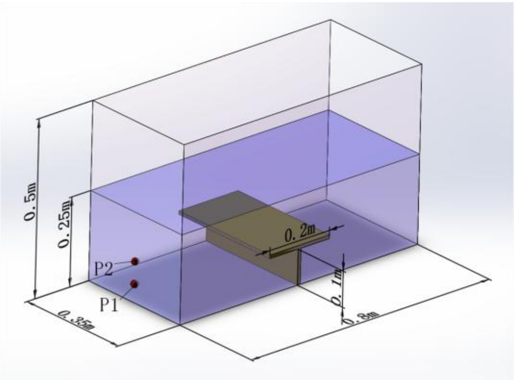

Fig. 5 The 3-D sketch of CASE 4

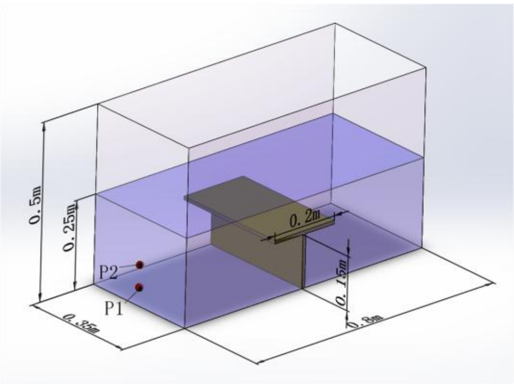

Fig. 6 The 3-D sketch of CASE 5

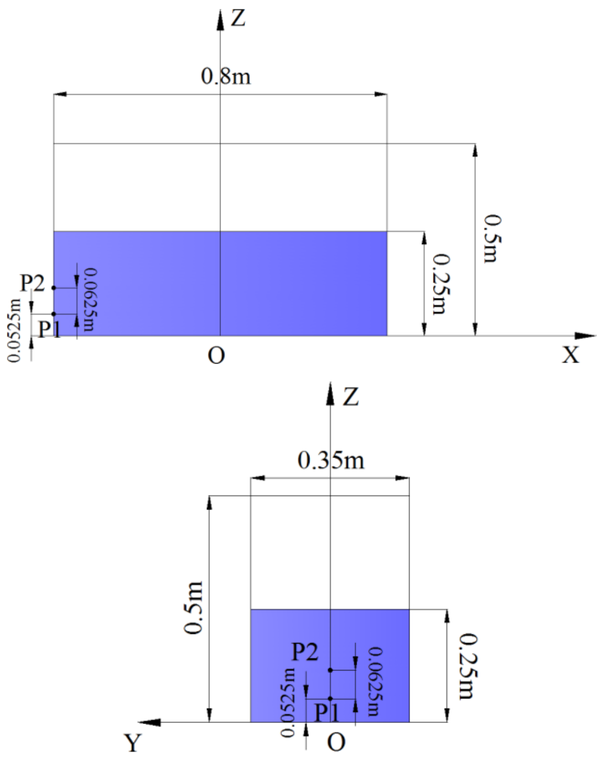

Fig.7 The layout of pressure probes (P1 and P2)

All models are subject to move by the external surge excitation:

$$X = A \cdot \sin(\omega \cdot t) \tag{11}$$

where A = 0.02 m is the surge amplitude, ω = 5.389 rad/s is the frequency of oscillation, which is same as the natural period of the fluid motion in the tank.

To model this problem, about 760000 particles are used. Corresponding particle space is dp = 0.005 m. The time step is $\Delta t = 5\times10^{-4}$ s. The acceleration of gravity is g = 9.8 m/s. The density of water is ρ = 1000 kg/m.

In addition, the variation of pressure on side wall is measured by two pressure probes (P1 and P2) shown in Figs. 2-7. And the arrangements of pressure probes (P1 and P2) are listed in Table 2.

Table 2 Arrangements of pressure probes (P1 and P2)

	X/m	Y/m	Z/m
P1	-0.4	0	0.0525
P2	-0.4	0	0.115

3.2 The Effects of Baffles on Liquid Sloshing

In this section, the effects of four different baffles (two vertical baffles and two T type baffles) on liquid sloshing are investigated. It is essential to note that, the validation of MLParticle-SJTU solver was conducted by [28]. For each CASE, four typical snapshots are captured in Figs. 8-12.

In CASE 1, the baffles are not placed. Many nonlinear phenomena such as overturning of free surface, breaking wave and splashing can be observed from Fig. 8. Comparing to Figs. 9-12, only the sloshing water of CASE 1 runs up along the vertical wall, impacts the roof of the tank and falls down under the action of gravity. In Fig. 8, the liquid sloshing without baffles is so violent that many peaks and troughs occur at the free surface, especially when the tank starts moving in opposite directions.

In CASE 2, the height of vertical baffle is 0.1 m. It can be seen from Fig. 9 that the sloshing amplitude is reduced. The phenomenon of overturning of free surface has already disappeared. But a little part of water still splashes. The vertical baffle obstructs most of the sloshing water effectively.

The height of vertical baffle is up to 0.15 m in CASE 3. Observing Fig. 10, the sloshing amplitude is further reduced. Almost all large deformation and nonlinear fragmentation of free surface have been disappeared. The height of water running up the side wall is much smaller than that in CASE 1 and CASE 2. Though the higher vertical baffle is more effective on restraining sloshing, a higher peak of the free surface compared to CASE 2 appears when the fluid flows over the vertical baffle. Maybe this phenomenon results from the baffle tip is too close to the free surface.

Base on CASE 2 and CASE 3, a horizontal baffle whose length is 0.2 m is placed at the top of vertical baffles, respectively. The snapshots of Figs. 11-12 show that this T type baffle is an effective way to restrain sloshing. By using T type baffle, the free surface is more smooth than applying vertical baffle. The deformation of free surface for CASE 5 is almost invisible by making a comparison to CASE 4.

Figs. 13-14 show the variations of pressures with time on P1 and P2. The results show that all kinds of baffles can reduce the pressure amplitude dramatically. Comparing CASE 1 with other cases, the pressure peaks of other cases lag behind that of CASE 1. The effect of these baffles on obstructing flow filed and restraining sloshing is remarkable. In addition, there are two successive pressure peaks in each period for CASE 1 and CASE 2, which can illustrate the liquid motion lags behind tank motion. The first pressure peak results from the liquid fiercely impacts the side wall. When the tank moves to the opposite direction with maximum horizontal displacement, the later water that washes up to the side wall results in the first high impact pressure. The large deformation of free surface such as overturning of wave and breaking wave results in the occurrence of second pressure peak. And this phenomenon of two successive pressure peaks can't be observed in CASE 3-5. The variations of pressures present rough sinusoidal curves for CASE 3, CASE 4 and CASE 5.

Fig. 15 compares the maximum impact pressure on the measuring probes P1 and P2 among these cases. It can be seen that the maximum impact pressures of P1 and P2 for CASE 2 are about 30% and 37% smaller than CASE 1, respectively. The vertical baffle plays an important role in retaining sloshing. Further, the maximum impact pressures of P1 and P2 for CASE 3 are about 300 Pa smaller than CASE 2. Thus it can be concluded that the higher vertical baffle is, the better effect on reducing impact pressure is. In

CASE 4, the maximum impact pressures of P1 and P2 are smaller than CASE 2, but little larger than CASE 3. Maybe increasing the height of vertical baffle is a more effective way to reduce pressure peak, comparing adding a horizontal baffle. Of course, the maximum impact pressures of CASE 5 are the smallest. Making a comparison between CASE 2 and CASE 4 or CASE 3 and CASE 5, the T type baffles are still more effective on reducing sloshing and impact pressure than vertical baffles.

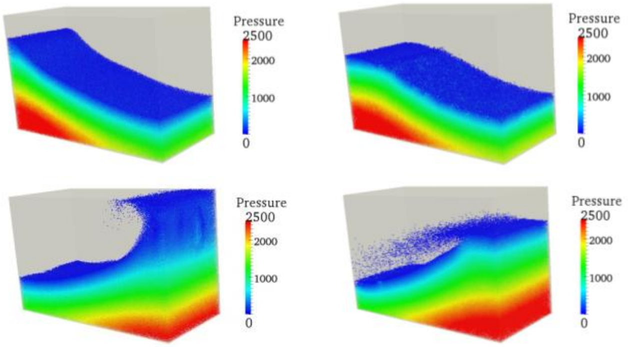

Fig. 8 The snapshots of CASE 1

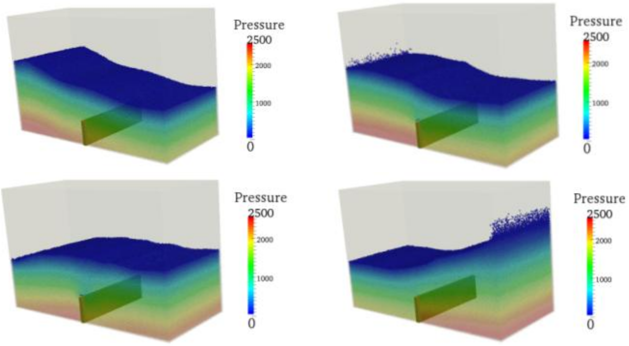

Fig. 9 The snapshots of CASE 2

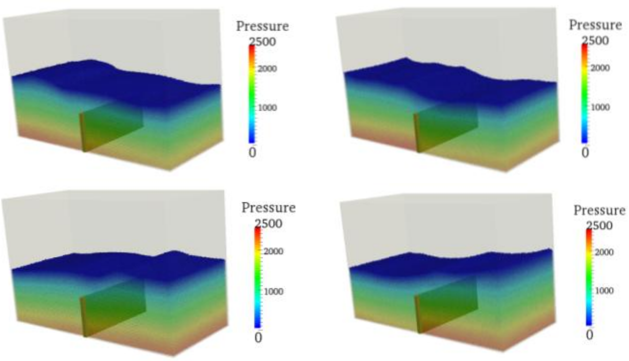

Fig. 10 The snapshots of CASE 3

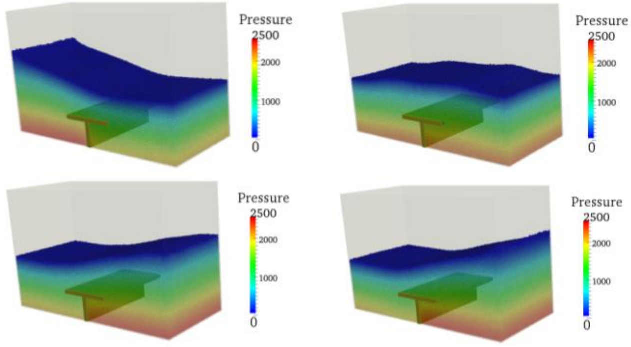

Fig. 11 The snapshots of CASE 4

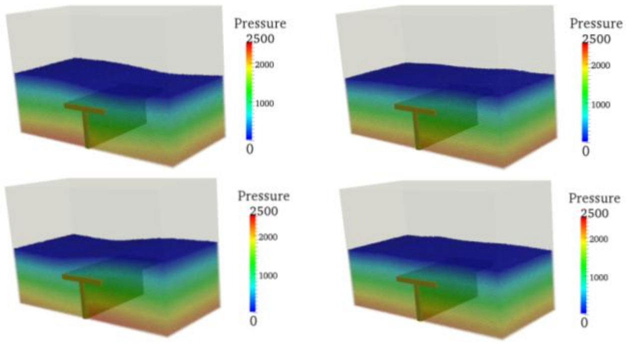

Fig. 12 The snapshots of CASE 5

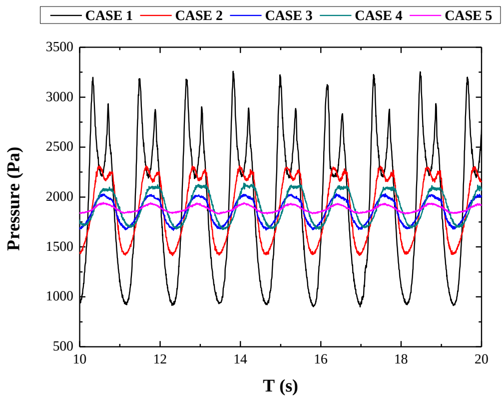

Fig. 13 The time history of pressure on P1

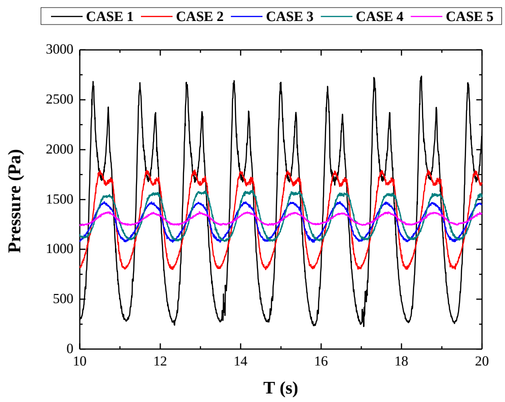

Fig. 14 The time history of pressure on P2

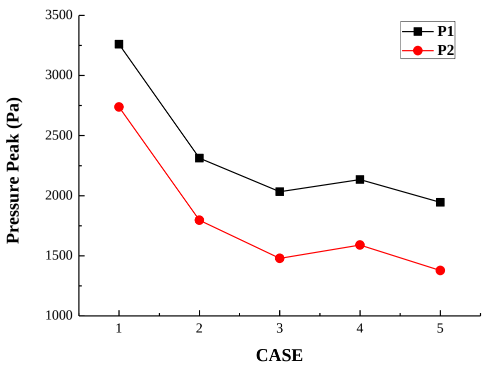

Fig. 15 Comparison of the maximum pressure on the measuring probes P1 and P2

4 Conclusion

In this paper, the effects of T type baffle on liquid sloshing are simulated numerically in 3-D tank by MLParticle-SJTU solver based on modified MPS method. The snapshots of flow field are captured and investigated. Two pressure probes are placed to measure the variation of pressure.

1) The liquid sloshing without baffles is so violent that large deformation and nonlinear fragmentation of free surface such as overturning of wave, breaking wave and splashing can be observed. And two successive pressure peaks appear in the pressure curve.

2) Comparing to no baffles, not only the vertical baffles but also T type baffles can reduce both sloshing and impact pressure amplitudes.

3) The height of vertical baffle plays a significant role in obstructing sloshing water. The higher vertical baffle is more effective on restraining sloshing. And the baffle tip influences the flow field.

4) It can be seen that the T type baffles can exert relatively more effectiveness on reducing violent liquid sloshing under the surge excitation than vertical baffles. The phenomena such as overturning of free surface, breaking wave and splashing have been disappeared by using T type baffles.

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