Numerical and Experimental Research on the Anti-sloshing Characteristic of Swash Bulkhead in LNG Independent Type C Tank

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Abstract. The sloshing induced by partial loaded in LNG (Liquified Natural Gas) independent type C tank will threat the structure of tank. For sloshing suppression, installation of swash bulkhead is a good choice. With model experiment, the sloshing suppression mechanism of perforated swash bulkhead is investigated. Comparing to the tank without swash bulkhead, the suppression efficiency is obtained. Base on the CFD (Computational fluid dynamic) theory, a numerical method is used to sloshing simulation of tank with perforated swash bulkhead, which is verified by the model experiment. Thus, with the same permeation ratio, the effect of anti-sloshing is analysed numerically with comparison of ring baffle and perforated bulkhead. It is found that perforated swash bulkhead has a better performance in sloshing suppression at higher filling level than the ring baffle. And there is a small variation in anti-sloshing efficiency of perforated swash bulkhead

1. Introduction

Liquid sloshing poses a great threat to the stability and structural strength of LNG vessel and tank. The loading limit and installation of swash bulkhead are employed to sloshing suppression in engineering. However, for making LNG tank in good working conditions, it has become a common method to use sloshing suppression device for restraining the motion of liquid and reducing the hazard caused by sloshing[1]. The perforated swash bulkhead is widely used in LNG independent type C tank due to its excellent performance in anti-sloshing[2]. The ring baffle is another choice of sloshing suppression device, which has advantage of simplicity of installation[3] and structure. Usually, the additional strengthening of independent type C tank, like T-bulb can act as the ring baffle.

There are several investigations, which is performed on anti-sloshing devices. Cho and Kim[4] investigated theoretically and experimentally the porous baffle in rectangular tank. It was found that the dual vertical porous baffles can significantly suppress sloshing motions when properly designed by selecting optimal porosity, submergence depth, and installation position. The optimal solidity ratio was given by Wei et al. with investigating the porous baffle in 2D rectangular tank under horizontal excitation. Liu et al.[5] had researched the parameters sensitivity of ring baffle in independent type C tank, including height, position installation, inclined angle, and thickness. It was found that in comparison to other parameters of ring baffle, increasing the height of ring baffle has the greatest influence on anti-sloshing.
Due to producing complex flow with installation of perforated swash bulkhead, the experimental study could be helpful to analyse the characteristic of sloshing suppression and validate the numerical method. In this paper, the model experiment is adopted to investigate the sloshing suppression mechanism of perforated swash bulkhead. The numerical method, which is based on CFD theory is employed to compute the sloshing pressure in the tank with perforated swash bulkhead, which is verified by model experiment. Then the ring baffle and perforated swash bulkhead is compared numerically by efficiency of sloshing suppression on the basis of same permeation ratio.

2. Experimental setup

2.1. Experimental Device

The independent type C tank is employed to investigated here. The volume of the tank is 1000 m³[6]. The ratio of the model tank to the full-scale tank is 1/17.8. The Fig.1 shows main parameters of the model tank: the total length ($L_t$) is 1.910m and inner diameter ($D_i$) is 0.380m. The test model tank includes main tank and head (see Figure 1). Thickness of the tank is 10 mm. The material of test model tank is plexiglas pipeline and PVC (polyvinyl chloride). The model tank has several holes for measuring sloshing pressure (shown as Figure 2). The experimental fluid is the water, which is dyed by red water-solubility.

![Figure 1. Numerical model for sloshing simulation](image)

Perforated swash bulkhead (shown as Figure 3) can be set into the test model tank. The perforated swash bulkhead of this experiment has 21 swash holes which is uniform distributed. The diameter of swash holes is 30 mm. Structural parameters of the perforated swash bulkhead is shown as Table 1, where permeation ratio is the ratio of area of swash hole to the whole area of bulkhead.

![Figure 2. Arrangement of pressure senor (unit: mm)](image)

![Figure 3. Model of perforated swash bulkhead (unit: m)](image)

| Parameters                        | value     |
|-----------------------------------|-----------|
| Outer diameter of bulkhead/m      | 0.38      |
| Diameter of swash hole/m          | 0.03      |
| Quantity of swash holes           | 21        |
| Area of swash hole/m²             | $1.58 \times 10^2$ |
| Permeation ratio/°                 | 13.09     |

The excitation motion for sloshing simulation is driven by a 6-DOFs (degrees of freedom) motion platform. Flush-mounted pressure sensors are employed to achieve loads induced by sloshing. Its
measuring ranges are 0–10 kPa. The accuracy of them 0.2% FS (full scale). The free-surface shape is traced by high-speed camera, which can record at 50 pictures a second.

2.2. Test case
It can be achieved that for this kind of shape of model tank longitudinal excitation induces sloshing easily. And for a ship, pitch is one of the most common situations[7]. In this study, pitch is selected to excite the test model tank. Three test cases are chosen to analyse the suppression sloshing mechanism of perforated swash bulkhead. Filling level, excitation frequency and excitation amplitude constitute the test case. Test cases are listed in Table 2, where \(f_n\) is the natural frequency of liquid on each filling level. The natural frequency is obtained by analysed the free oscillation of experimental fluid with the Fast Fourier transform.

| Case | Filling level | Excitation frequency | Excitation amplitude /rad |
|------|---------------|----------------------|---------------------------|
| No. 1 | 0.40\(D_t\)  | \(f_n\) (0.28 Hz)    | 0.052                     |
| No. 2 | 0.60\(D_t\)  | \(f_n\) (0.36 Hz)    | 0.052                     |
| No. 3 | 0.80\(D_t\)  | \(f_n\) (0.48 Hz)    | 0.087                     |

3. Analysis of experimental result

3.1. Free surface shape
The free surface shape of liquid in test model tank are shown as Figure 4–6. It can be found that the perforated swash bulkhead could suppress the motion of liquid significantly. The motion of test model tank is in a quarter period. The excitation angular velocity reaches its maximum. The liquid in the tank, in which the swash bulkhead isn't set, flows with in the form of a bore[8]. At the filling level of 0.8\(D_t\), the liquid flows to the top of head and break into droplets after swirling. After installing the perforated swash bulkhead, the liquid will flow mildly. The wave transformed into the standing wave. The fluctuation of free-surface is small. And there will not form the height difference between liquid in two sides of tank.

![Figure 4. Comparison of free surface shape (case No.1)](image)

![Figure 5. Comparison of free surface shape (case No.2)](image)
3.2. Sloshing pressure

The monitoring points P1S, P2, P3, P4, P5 are selected to compare the sloshing pressure in the tank with or without swash bulkhead. These points are located near the free-surface of each filling level. The sloshing pressure of each points are drawn in Figure 7–9, where $P_{\text{W BH}}$ and $P_{\text{BH}}$ are the sloshing pressure in normal tank and in tank installed swash bulkhead, respectively. It can be seen that the curve of sloshing pressure in tank with swash bulkhead has a single peak. While in normal tank, there is a double peak in every period, especially, at the higher filling level. As the excitation frequency is close to the natural frequency, the impact pressure due to the violent motion of the free surface will be dominant and the first peak will be formed. Then, when the tank moves to the horizontal position, the liquid will push the tank head due to inertial force and gravity. Thus, it will produce the other peak[5]. Therefore, due to the installation of swash bulkhead, the motion of the free surface is suppressed significantly.

![Figure 6. Comparison of free surface shape (case No.3)](image)

![Figure 7. Comparison of anti-sloshing efficiency (case No.1)](image)

![Figure 8. Comparison of anti-sloshing efficiency (case No.2)](image)
The mean and maximum pressure in sloshing pressure are calculated (shown as Table 3). It can be concluded that the perforated swash bulkhead performed the best at the filling level of 0.4D_i. Compared to the sloshing pressure in the normal tank, the maximum value and mean value of sloshing pressure decrease at 69.99% and 76.45%, respectively. Meanwhile, the pressure of monitoring points at free-surface reduce most compared with other monitoring points. The bulkhead increases the damping of liquid flow, which restricts the motion of the free surface more than other zones in tank.

**Table 3.** Quantitative analysis of anti-sloshing performance

| Case No.1 | Sloshing pressure/Pa | | | | |
|---|---|---|---|---|
| | $P_{\text{max}}$ | $P_{\text{mean}}$ | | |
| | P1S | P2 | P1S | P2 |
| Tank without swash bulkhead | 1749.94 | 1319.17 | 643.36 | 362.62 |
| Tank with swash bulkhead | 871.49 | 395.83 | 460.34 | 85.39 |
| Efficiency of suppression/% | 50.20 | 69.99 | 28.45 | 76.45 |
| Case No.2 | P3 | P4 | P3 | P4 |
| Tank without swash bulkhead | 1176.14 | 1033.33 | 411.68 | 241.23 |
| Tank with swash bulkhead | 735.16 | 453.33 | 332.41 | 123.19 |
| Efficiency of suppression/% | 37.49 | 56.13 | 19.25 | 48.93 |
| Case No.3 | P4 | P5 | P4 | P5 |
| Tank without swash bulkhead | 2499.01 | 1801.67 | 848.50 | 232.60 |
| Tank with swash bulkhead | 1343.19 | 628.41 | 695.22 | 135.64 |
| Efficiency of suppression/% | 46.25 | 65.12 | 18.06 | 41.68 |

4. Numerical analysis of perforated swash bulkhead and ring baffle

4.1. Numerical method and model

The lengthwise direction of tank and direction of gravity is set as x and y coordinate, respectively. Thus, the tank rotates about the z axis. The numerical model can be described as Figure 10.
Figure 10. Numerical model for sloshing simulation

The viscous fluid sloshing is subject to a continuity equation and the Navier-Stokes equation. The ideal gas is employed to simulate the air in the tank. Hence, the governing equation also includes the conservation of energy equation. So the governing equations can be listed as follows.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0, \quad (1)
\]

\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j}\left( -\rho u_i u_j \right), \quad (2)
\]

\[
\frac{\partial}{\partial t}\left( \rho e + \frac{u_i^2}{2} \right) + \nabla \cdot (\rho u_i (e + \frac{u_i^2}{2})) = \nabla \cdot \left( \kappa_{\text{eff}} \nabla T \right) + \nabla \cdot (\nabla \cdot (\mu \cdot \nabla u_i)) + \rho f_i u_i + S_k, \quad (3)
\]

Where \( p \) is the time averaged pressure; \( \mu \) is the dynamic viscosity of water; \( \delta_{ij} \) is the Kronecker delta; \( -\rho u_i u_j \) is the Reynolds stress term; subscripts \( i, j, \) and \( l \) are the coordinate directions. \( e \) is the internal energy, \( \kappa_{\text{eff}} \) is the effective thermal conductivity, \( \nabla T \) is the temperature gradient, \( f_i \) is the body force vector, and \( S_k \) is the source term.

For reducing the computational expense, the realizable \( k-\varepsilon \) turbulence model is employed. The turbulent kinetic energy \( k \) and its rate of dissipation \( \varepsilon \) are achieved by the following equation.

\[
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[ \mu \frac{\partial k}{\partial x_j} \right] + f_i G_i + G_b - \rho (\varepsilon - \varepsilon_0) - \gamma_M + S_k, \quad (4)
\]

\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[ \mu \frac{\partial \varepsilon}{\partial x_j} \right] + f_i C_{\varepsilon} S_k + \frac{\varepsilon}{k} (C_{\varepsilon} C_{\varepsilon}, G_k) - \frac{\varepsilon}{k + \sqrt{\varepsilon}} C_{\varepsilon}, \rho (\varepsilon - \varepsilon_0) + S_\varepsilon, \quad (5)
\]

where \( \mu_t \) is the eddy viscosity coefficient; \( G_k \) is the turbulent production term; \( f_i \) is the curvature correction factor; \( G_b \) is the buoyancy production term; \( \varepsilon_0 \) is the ambient turbulence value in the source terms that counteracts turbulence decay; \( \gamma_M \) is the compressibility modification term; \( S_k \) and \( S_\varepsilon \) are user-specified source terms. \( C_{\varepsilon 1}, C_{\varepsilon 2}, \) and \( C_{\varepsilon 3} \) are the constant coefficients. \( \alpha_1 \) and \( \sigma_1 \) are the turbulent Prandtl numbers for \( k \) and \( \varepsilon \), respectively. \( S \) is the modulus of the mean strain rate tensor. \( \nu \) is the kinematic viscosity.

The volume of fraction (VOF) method is employed to capture the free surface. According to the numerical model, the fluid is divided into two phases, each of which can be written as the following equation.

\[
\frac{\partial \alpha_q}{\partial t} + \nabla \cdot (\alpha_q u) = 0, \quad (6)
\]

where \( \alpha_q \) is the \( q \)th phase, and all phases are based on the following constraint.

\[
\sum_{q=1}^n \alpha_q = 1, \quad (7)
\]

4.2. Verification
The numerical method is verified by comparing the free-surface shape and pressure time history of sloshing in experiment. The condition is selected, in which the test model tank is installed with perforated swash bulkhead. The verification case is No.2, the parameters of which is listed in Table 2. The Cartesian grid is used to mesh the model (see Figure 11). The refinement process is applied to the boundary, free-surface and perforated swash bulkhead. The half model is established and the vertical section is set as symmetrical. After the analysis of grid and time step independence, the quantity of grid and time step is selected as 637 thousand and 0.002s, respectively.

**Figure 11. Gird model of the tank**

The results of verification are shown in Figure 12 and Table 4. It is found that the numerical profile of the free surface generally coincided well with the experimental profile. Likewise, the curves of pressure time history show good agreement in the case validated.

**Figure 12. Comparison of free surface shape**

4.3. Comparison of anti-sloshing performance

Based on the same permeation area (Table 2), the structural parameters of ring baffle is determined. The comparison of structural parameters is listed in Table 4, where the permeation ratio is the ratio of permeation area and the whole area of swash bulkhead. The ring baffle is also installed in the middle of the tank.

**Table 4. Comparison of structural parameters**

| Form of swash bulkhead | Diameter of swash hole/m | Height of ring baffle/D_i | Permeation area/m^2 | Permeation ratio/% |
|------------------------|--------------------------|----------------------------|---------------------|-------------------|
| Perforated             | 0.4                       | -                          | 2.64x10^{-2}        | 23.27             |
| Ring baffle            | -                         | 0.31                       | 2.66x10^{-2}        | 23.45             |

The efficiency of swash bulkhead is taken from the definition of the reference[3]. However, in this paper the water height variation in the equation is replaced by the horizontal force on the head due to liquid sloshing. Thus, the efficiency of the ring baffle is defined as

\[
\eta_{\text{anti-sloshing}} = \frac{\sigma_{\text{unbaffled}} - \sigma_{\text{baffled}}}{\sigma_{\text{unbaffled}}},
\]

(8)
where \( \sigma \) is the square of deviation of force in \( x \) direction at the left head, and the subscript of \( \sigma \) specifies sloshing condition of tank with or without swash bulkhead.

The force time history on the head of the tank in the \( x \) direction is achieved in numerical simulation. Finally, the anti-sloshing efficiency of two kinds of swash bulkhead is listed in Table 5, and the corresponding curve graph is shown as Figure 13. It can be found that the sloshing suppression performance of ring baffle is better than perforated swash bulkhead, when the filling level is lower than 0.5\( D_i \). However, the anti-sloshing efficiency of the two swash bulkheads is almost the same under the filling level of 0.25\( D_i \). When the filling level exceed the half loaded, the sloshing suppression efficiency of ring baffle will decrease. And the anti-sloshing efficiency of ring baffle has a larger variation on each filling level. The lack of fluid motion suppression in middle of ring baffle is the main reason.

Table 5. Comparison of anti-sloshing efficiency

| Filling level/\( D_i \) | \( \sigma_{WBH} \) | Perforated | Ring baffle |
|------------------------|-----------------|------------|-------------|
|                        | \( \sigma_{BH} \) | \( \eta_{anti-slosh\%} \) | \( \sigma_{RB} \) | \( \eta_{anti-slosh\%} \) |
| 0.25                   | 7.80            | 3.28       | 57.95       | 2.59         | 59.09         |
| 0.40                   | 17.67           | 8.79       | 50.24       | 3.70         | 53.72         |
| 0.60                   | 27.21           | 16.27      | 40.23       | 12.58        | 36.64         |
| 0.80                   | 36.97           | 19.69      | 46.73       | 27.34        | 26.93         |

Figure 13. Graph of anti-sloshing efficiency

5. Conclusion

With model experiment, the sloshing suppression mechanism of perforated swash bulkhead is investigated. It can be proved that the perforated swash bulkhead could well restrain the motion free-surface and the impact force of fluid is decrease significantly. The bulkhead performed best under the filling level of 0.4\( D_i \). The sloshing pressure near the free-surface is reduced by an average of 76.45\%. Based on the same permeation ratio, the effect of anti-sloshing is analysed numerically with comparison of ring baffle and perforated bulkhead. With comparison of free-surface shape and sloshing pressure in the experiment, the numerical method is verified to have a good accuracy in anti-sloshing simulation.

The characteristic of anti-sloshing of ring baffle and perforated swash bulkhead is analysed. It can be concluded that ring baffle could suppress fluid sloshing better in the lower filling level. However, the perforated swash bulkhead has a good performance in sloshing suppression at all filling level. Thus, it is suggested that perforated swash bulkhead could be installed where the tank has a great change in filling ratio, like fuel bunker vessel.

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