Transient Response Analysis of Multi-layer Sloshing Fluid in LNG Tank

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Abstract. The stratified LNG is the potential cause of rollover, so the analysis of the interface behavior is very important. In this work, a three-layer dynamic simulation model of BOG, LNG, and liquid nitrogen of sloshing stratified LNG in a tank was built. The transient behaviors of the layers were simulated, and the effects of factors such as the period of sloshing (T = 0.2, 0.4, 0.6, 0.8 and 1.0 s) and the amplitude of sloshing (A=0.01~0.06 rad) were analyzed. It was found that instability of the interface was aggravated over time. There was a specific period of sloshing in which the layers of fluid were relatively stable, away from this period the fluid layer became less stable. The influence of sloshing amplitude on the behavior of the interface presented a wave characteristic. The simulation results of the coupling with different sloshing periods and sloshing amplitude showed that the interface behavior of stratified sloshing was the most severe when the sloshing period was 0.2 s and the sloshing amplitude was 0.05 rad.

1. Introduction
Liquefied natural gas (LNG) rollover incidents were recurrent over the last 60 years, 24 rollovers were reported by the GIIGNL group[1]. Whereas there had been a rapid increase in LNG rollover accidents on Floating Storage and LNG carriers in the past ten years, these accidents were correlated mainly to frequent refilling or frequent movement of LNG storage tanks during transportation[2]. Consequently, rollovers are currently considerably more frequent on floating storage or LNG ships and present a more frequent safety risk[3].

Rollover is a phenomenon that can occur in systems containing stratified liquids. During LNG storage or transportation, due to the improper filling methods. The nitrogen mixing and the addition of new batch liquid of LNG to the existing LNG quantity in a tank all can form a stratification of two or more layers within the storage tank, which can form obvious interfaces and may cause a rollover phenomenon[4]. The evolution of stratified LNG to consist of two principal phases before arising a rollover phenomenon: stable phase 1 where the interface between the two layers is stationary; and an unstable phase 2 characterized by a migrating interface and culminating into a rollover[5]. The release of the heat trapped in the lower layer results in the rapid generation of Boiling Off Gas (BOG), accompanies by the ultimate breakdown of the stratified interface[6]. However, the results of the numerical study showed that the time of reaching the peak of generating BOG was shortened and the rollover phenomenon was prepositioned with the increase of sloshing degree under the condition of sloshing in the LNG storage tank[7]. Therefore, it is necessary to consider the effect of sloshing on the rollover of stratification.
Currently, theoretical analyses, numerical analyses, and experimental researches on the actual transport conditions of the tank had made more achievements [8, 9]. Research demonstrated that the behaviors of the interface under the sloshing state were related to the tank shape, filling-liquid ratio, excitation frequency, and amplitude. The experiments and numerical analyses of the tank with different shapes under different sloshing frequencies were carried out. The results showed that the excitation frequency directly affects the response of the liquid interface, and the interface instability behavior was the most obvious under the frequency of parametric resonance. What’s more, study on sloshing behavior of liquid in LNG tank indicates that there were many kinds of nonlinear behaviors of liquid sloshing caused by external excitation, including traveling wave, standing wave, the wave rolling over the wall, splashing of the interface, and breaking of the interface. However, the researches focused on the LNG sloshing flow problem for a single LNG fluid layer, without considering the free interface sloshing behavior of the multi-stratified LNG layers. The free interface behavior of multi stratified fluid in LNG tanks based on dynamics needs to be further studied.

In this paper, the calculation model of the free interface behavior of the fluid inside the tank with three stratified layers was established, and the stratified sloshing behaviors under coupling conditions were simulated. The entire internal space of the sloshing tank was treated as the computational region, and the RNG k-epsilon turbulence model was employed. The Volume of Fluid (VOF) method was applied to capture sloshing liquid surface. The effects of different sloshing durations, periods (T = 0.2, 0.4, 0.6, 0.8, and 1.0 s), and amplitudes (A=0.01-0.06 rad) on the fluctuation height range, the instability behavior of gas-liquid interface, and liquid-liquid interface in the tank were analyzed.

2. Numerical model

The commercial software was applied to simulate the sloshing behavior of the fluid in an LNG tank under different angular velocities. The external excitation of sloshing was realized by dynamic grids. The liquid inside the tank was set as the incompressible viscous fluids, without considering the energy variation of the internal fluid in the sloshing process.

The physical model of the LNG tank is complex, only the liquid stratification with a large difference in liquid partial density was considered. The upper layer is the low-temperature fluid and the lower layer is the high-temperature liquid. Therefore, as shown in Fig.1, a three-layer model of an LNG storage tank with BOG-LNG-liquid nitrogen was established according to the nitrogen-mixing model in the LNG tank.

2.1 The RNG k-epsilon turbulence model

The mass conservation equation is as follows:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_\rho \]  

\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla \cdot (\rho \mathbf{g}) + \rho \mathbf{g} + \mathbf{F} \]  

\[ \frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{v} k) = \nabla \cdot \left[ \alpha_k \mu \frac{\partial k}{\partial x} \right] + G_k + G_b + \rho \varepsilon - \frac{\partial \varepsilon}{\partial x} + S_k \]  

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \mathbf{v} \varepsilon) = \nabla \cdot \left[ \alpha_\varepsilon \mu \frac{\partial \varepsilon}{\partial x} \right] - \frac{\varepsilon}{k} \left( G_k + C_{1\varepsilon} \varepsilon \right) - C_{2\varepsilon} \rho \varepsilon \frac{\varepsilon^2}{k} + S_\varepsilon \]  

In the RNG k-epsilon turbulence model, the turbulent viscosity in the high-Reynolds number is calculated by the following equation:

\[ \mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \]  

Where \( C_\mu \) is a constant; \( k \) is turbulent kinetic energy; \( \varepsilon \) is turbulent dissipation rate; \( G_k \) is the generation of turbulence kinetic energy by the mean velocity gradients; \( G_b \) is the generation of turbulence kinetic energy by buoyancy; \( Y_M \) is the contribution of the fluctuating dilatation; \( S_k \) is the user-defined source term for \( k \); \( S_\varepsilon \) is the user-defined source term for \( \varepsilon \).
2.2 Natural frequency and sloshing excitation equation

The natural frequency is related to the parameter of the tank, including the depth of the liquid and the length of the excitation direction of the free interface. The Cartesian coordinate system was established with the center of the circular section of the LNG tank as the origin O, as shown in Fig.2. Obtaining the natural frequency equation of the tank \[12\] as follows:

\[
f_n = \frac{1}{2\pi} \sqrt{\frac{gh}{l}} \left(\frac{n\pi}{l} h\right), (n = 1, 2, 3, \ldots)
\]

Where \(l\) is the length of the free interface (m); \(h\) is the height of liquid (m); \(n\) is the modal order number.

Figure 1. Physical model of the storage tank. Figure 2. The calculation model of the LNG storage tank.

| motion model | Frequency \(f\) (Hz) | Period \(T\) (s) | Amplitude \(A\) (rad) |
|--------------|----------------------|----------------|------------------|
|              | 5.0                  | 0.2            | 0.01             |
|              | 2.5                  | 0.4            | 0.02             |
|              | 1.67                 | 0.6            | 0.03             |
|              | 1.25                 | 0.8            | 0.08             |
|              | 1.0                  | 1.0            | 0.04             |
|              |                      |                | 0.05             |
|              |                      |                | 0.06             |

The sloshing behavior of the tank was mainly caused by the process that the tank is excited around a certain point. Due to the complexity of the LNG tank in actual work, it was necessary to conduct numerical research on the tank under different sloshing periods and amplitude.

In the tank design rule of the LNG tank, the longitudinal baffles were required to suppress longitudinal sloshing of fluid in the tank \[14\]. Therefore, only fluid sloshing caused by a horizontal sloshing tank was considered. The excitation equation was applied to simulate various working conditions of LNG tank sloshing. The angular velocity equations of the LNG tank around the sloshing center (Fig 2.) were shown as follows.

\[
W_z = A \cos \left(\frac{2\pi}{T} t\right)
\]

Where \(W_z\) is the angular velocity rotating around the Z-axis (rad/s); \(A\) is the amplitude (rad); \(T\) is the period (s).

3. Calculation model and numerical method validation

As shown in Fig 3, the radius of the model of the two-dimensional storage tank was 1000 mm, the initialized values of the volume ratio of BOG, LNG, and liquid nitrogen in the internal fluid were 5 %, 85 %, and 10% respectively, and the filling liquid ratio was 95%. Because the density of liquid nitrogen is larger than that of LNG, liquid nitrogen will sink at the bottom of the storage tank, and a three-layer model was established, as shown in Fig 1. The upper layer was BOG, the middle layer was LNG, and the lower layer was liquid nitrogen. In the initialization, it was considered that the interface of each layer is an ideal plane layer.

3.1. Model setting

The wall was the non-thickness wall. The internal fluid was divided into three layers, and the initial distribution was shown in Fig 2. The influence of temperature on the pressure change was ignored.
Considering the actual sloshing excitation conditions in the process of LNG tank transportation, the sloshing actual conditions of the vessel were analyzed, and the excitation vessel motion parameters were obtained as follows the Table 1, a total of 30 cases. Considering the calculation accuracy, the PISO algorithm in the non-coupled implicit algorithm based on pressure solution was applied to solve the problem, and the RNG k-ε model was employed for calculation.

3.2. Validation
The experimental data of the free surface velocity was carried out by Chiba et al.\textsuperscript{[15]}, were utilized for the validation of the model. As shown in Fig. 3, the inner radius of the sphere was 0.1425 m, and the filling ratio was 50%. The vertical sinusoidal excitation is shown in formula (8), and the \( f \) was 5.8 Hz, the \( G \) was 0.06. The velocity of the response wave measured at the flange of the tank was compared in Fig. 3, which showed a good agreement between the experimental data and the present numerical results.

\[
Z = \frac{G}{2\pi f} \sin(2\pi ft)
\]  

(8)

Where \( G \) is the ratio between the excitation acceleration and gravitational acceleration.

![Figure 3. The model parameters and the comparison of the time history of response wave velocity at P1 between the experimental data from Chiba et al. (2016) and the present numerical results.](image)

4. Results and discussion
The simulation results of 30 cases in Table 1 were analyzed. The transient response behaviors exposed to two different types at the liquid-liquid interface. Fig.4 (a) and (b) exhibited these transient response behaviors at the liquid-liquid interface, such as interface tilt and wave rolling in the zone close to the wall, that the distribution condition as Table 2. The influence of sloshing on the instability of the upper gas-liquid interface in the tank was more significant than that of the lower liquid-liquid interface while the period and amplitude were constant.

![Figure 4. The transient response behaviors of the Liquid-liquid interface.](image)
Figure 5. The liquid-liquid interface evolved in the form of the wave rolling in the zone close to the wall.

Figure 6. The liquid-liquid interface evolved in the form of interface tilt.

Table 2. Distribution of the transient response behaviors.

| Distribution | Gas-liquid interface | Liquid-liquid interface |
|--------------|----------------------|-------------------------|
|              | Interface splash and breakup | Wave rolling in the zone close to the wall |
|              | Interface tilt | Tilt of interface |
| Period $T$ (s) | 0.2 - 0.6 | 0.2 - 0.4 | 0.4 - 1.0 |

Figure 7. The effect of amplitude on the liquid-liquid interface.

Figure 8. The effect of the period on the liquid-liquid interface.

4.1 The liquid-liquid interface

4.1.1 Duration of sloshing

To reveal the underlying sloshing dynamics, Fig. 6 showed the time history of the liquid-liquid free surface elevations. The instability exhibited an increasing exacerbation, which was mainly manifested as the interface tilt and wave rolling in the zone close to the wall. The height of wave increased gradually with the sloshing of the tank, and tilt angle of the interface had the similar trend.

4.1.2 Amplitude

Fig.7 exhibited that the effect of amplitude on the liquid-liquid interface was mainly divided into three phases by the surface height differentials, as following:
Phases 1: The height differentials showed a rapid downslope trend when the amplitude between 0.01 rad and 0.02 rad;
Phases 2: As the amplitude was from 0.03 rad to 0.05 rad, the height differentials presented as an upward trend accompanied by fluctuations;
Phases 3: There was a decreasing trend again, but the rate less than phase 1.

Fig. 7 illustrated that the height differential within relatively a small range when the amplitude was 0.02 rad, 0.03 rad, and 0.06 rad. Through comprehensive analysis, the amplitude of 0.02 rad considered was the most stable phase of the liquid-liquid interface, which was adverse to generate the rollover of stratification.

4.1.3 Period

Fig. 8 illustrated the effect of the period on the liquid-liquid interface by the height differentials, which were presented in two phases. Phase 1 under the main interface behavior of the wave rolling in the zone close to the wall, which the period was between 0.2 s and 0.4 s. Consequently, the height differentia was over a wide range and the maximum over 10 cm. Phase 2 was the height differentials caused by the tilt of the liquid-liquid interface. Hence, the stability of interface behavior was strengthened with the extendibility of the period and the height differentials were only between 0 cm and 3 cm. However, the lengthened response time between the left and right limit positions engendered a slight increase in the inclination angle of the liquid-liquid interface after the period over 0.6 s. Overall results as explained in Fig. 8, the minimum height differential was displayed in the sloshing period of 0.6 s, this meant that the LNG-liquid nitrogen interface arrived at the most stable state.

4.2 Analysis on results of coupling conditions

By concluding the results in chapters 4.1.2 and 4.1.3, the region of sloshing period and sloshing amplitude that had the least influence on the gas-liquid and liquid-liquid interfaces were obtained respectively. Comprehensive overall results that the amplitude region between 0.02 rad and 0.03 rad and the period of 0.6 s was conducive to weakening sloshing behavior. To reveal the effect of sloshing dynamics on a rollover in real transportation, the free surface elevation at various times of the cylindrical tank under the single degree of freedom horizontal excitation was further examined. The transient response behavior of the upper and lower free interface was the most stable under the condition of period 0.6 s and amplitude 0.02 rad, and it was the most exaggerative when the period was 0.2 s and the amplitude was 0.05 rad, which was expressed as Fig. 9.
5. Conclusions

The LNG stratified sloshing simulation model was established and validated. The effects of the sloshing dynamics on the transient response behavior of the free surface in the tank were investigated numerically. The interface tilt and wave rolling in the zone close to the wall were exposed to the liquid-liquid free interfaces respectively. The variation law of the free interface sloshing was surveyed, the conclusions drawn from this study can be summarized as follows.

1) Liquid sloshing promoted the risk of the free interface breaking and accelerated the generation of a rollover, especially in the early stages of motion. Long-time sloshing aggravated the transient response behaviors of the free interface, which is not conducive to the stable storage of multi-layer fluid in the LNG storage tank.

2) Representation of the free surface response by the height differentials. The effect of the sloshing amplitude represented a fluctuating trend. Based on the synthetical study, it was concluded that the amplitude around 0.02 rad had the minimum impact on interface motion. The sloshing period (T=0.6 s) motivated a minimum magnitude of interface sloshing.

3) Within the case study scope under this size of the tank, the fluid sloshing to the most violent state at the conditions of T=0.2 s and A=0.05 rad. Consequently, to reduce the potentiality of a rollover, the most violent sloshing condition should be avoided in the design of inhibiting the tank motion equipment.

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