Thermodynamic Response Analysis of Sloshing Ship in Marine LNG Storage Tank

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Abstract

Under the influence of the external environment, the influence of the liquid sloshing force in the LNG low-temperature storage tank of the marine ship storage and transportation, and the loss of LNG in the storage tank due to the evaporation phase change. According to the thermodynamic characteristics in the storage tank, the mechanism of phase transformation of LNG is analyzed, the structure of LNG storage tank is optimized, and theoretical guidance is provided for its safety maintenance. Based on the theory of computational heat transfer, based on the simplified LNG storage tank, the numerical analysis of the fluctuation of free surface, the force of the wall and the mass transfer rate of LNG are studied. The leakage heat, sloshing amplitude and liquid level in different externalities are studied. The dynamic response process of LNG loss and internal force in the tank at height and frequency. The external leakage heat rises, the amplitude and frequency increase, and when the LNG liquid level in the tank is low, the LNG evaporation loss rate increases.

Keywords

LNG storage tank; Thermodynamic analysis; Sloshing process; Low temperature phase transition.

1. Introduction

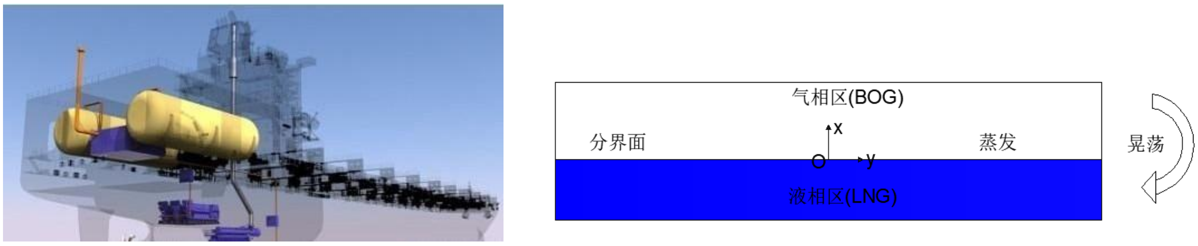
Due to the large-scale use of fossil fuels, atmospheric and marine environmental pollution is becoming more and more serious. LNG is widely used as a next-generation alternative clean fuel, and the demand for ships is increasing. Natural gas is required to be cooled to -162 °C for storage and transportation, and the natural gas from gaseous to liquid is denser and less sticky. When transported at sea, the sloshing of the ship will drive the LNG to slosh together. For the special equipment such as LNG power fuel tank, as the liquid level in the tank continues to decrease, the fluctuation of the induced free liquid level will be more severe, and the LNG liquid will be grooved. The beating of the wall of the can produces a greater impact. The huge temperature difference between LNG and the external environment at low temperature makes the leakage heat more easily invaded and absorbed, and the LNG undergoes thermal phase transformation to produce BOG. In addition to the sloshing of the liquid, the thermal response in the tank is more unstable and difficult to predict. Based on the theory of computational heat transfer [5], the internal mechanism and the influence of sloshing are studied, and sufficient preparations are made for the design of prevention equipment and theoretical guidance in the future.

Researchers at home and abroad have also done a lot of work on the research of LNG technology. Before I started the research of this topic, I also carefully read and studied the relevant literature. (LEE.DH, 2007) The effects of different parameters on the load of LNG tanks were studied by numerical simulation. Different density, viscosity and viscosity models were tested. The main analysis was the change of pressure and water level. No consideration is given to cryogenic liquids and external heat leaks [4]. (Roh S, 2013) used the numerical simulation theory to calculate the transient natural convection phenomenon when the gas pressure in the LNG storage tank increases, and the effect of gas phase pressure on LNG evaporation is obtained [1]. The change will have a certain impact on the LNG phase transition. Under the sloshing conditions of this paper, the pressure change in the gas phase zone is temporarily not considered, and the case of pressure fluctuation in the liquid phase and the gas phase will be considered in the later stage. (LEE.H.B, 2011) analyzed the evaporation phase transition process of LNG after leaking from storage chamber to long-term insulation cotton [2]. (Liu Zhan, 2018) Considering the hydrodynamic characteristics of cryogenic liquid oxygen storage tanks at different amplitudes, a series of numerical simulations were carried out in this case. The sloshing process is a non-adiabatic process accompanied by a gas condensation process [3]. (He Xiaocong, He Rong, 2016) The numerical simulation was used to analyze the impact force and the effect of the anti-wave plate on the marine LNG storage tank under different sloshing conditions [6]. This paper analyzes the vaporization of LNG cryogenic liquid and the mechanical properties of LNG storage tank under ship sloshing.

2. Modeling Construction

The research object of this paper is 3.7m long and 1.2m in diameter. The front and back ends are semi-circular heads. The LNG storage tank with a radius of 0.6m is the research object. Figure 1 shows the 2d cross-section of the numerical calculation. Some special equipments arranged outside and inside the tank are neglected, mainly focusing on the analysis of the internal LNG thermal response characteristics of the tank.

In order to better analyze the state of the fluid, some pressure detection points are arranged inside the tank to monitor the pressure changes at some locations. The fluctuations of the liquid level on the wall and inside and the impact on the wall are also calculated. And torque. The monitoring position is as shown. The sloshing center is at the origin, the initial liquid level is 0.6m, which is half of the total volume, and the external environmental pressure and temperature are 101325Pa and 300K, respectively.



a）LNG Storage Tank Layout b）2D Sectional View

Fig1 Martine LNG Storage Tank Schematic Diagram

Monitoring point and line placement coordinates：

Table 1 Monitoring point and line position

Point	Coordinates	Line	Position
P1	(-1.85,0.3)	L1	X=-1.3875
P2	(-1.85,0)	L2	X=-0.925
P3	(-1.85,-0.3)	L3	X=0

3. Mathematical Model

3.1 Conservation Equation

The free liquid surface inside the LNG storage tank will be moved and changed by the external shaking. In this paper, the mass conservation equation and the volume function equation are established to solve the volume content and distribution of the gas and liquid phases, and then the shape and variation of the gas-liquid interface are accurately determined:

$$\frac{\partial\rho}{\partial t}+\nabla\left(\rho\vec{v}\right)=S_m . \tag{1}$$

$$\alpha_l+\alpha_v=1 . \tag{2}$$

α_l and α_v are volume fractions of the gas phase and the liquid phase, respectively. Sm is the mass source phase. Considering that the phase transition occurs after the LNG reaches the saturation temperature, the actual process involves evaporation and condensation. The source phase acts on the entire fluid region, and the phase change affects both the gas-liquid interface and the reservoir. On the inner wall,The phase change model uses the LEE model as follows:

$$s_m = \begin{cases} r_l \alpha_l \rho_l \left(T_l - T_{sat} \right) / T_{sat}, T_l \geq T_{sat} \\ r_v \alpha_v \rho_v \left(T_v - T_{sat} \right) / T_{sat}, T_v < T_{sat} \end{cases} . \tag{3}$$

r_l and r_v are mass transfer intensity factors, and the specific values are compared according to different experimental values. The default value is 0.1.

Due to the influence of static pressure, the LNG saturation temperature will also change in response. The change relationship is based on the internationally renowned thermal property software NIST, compiled into a numerical calculation program using UDF, and the saturation temperature and saturation pressure of LNG are calculated. The function relationship is as follows:

$$T_{sat} = 0.3709e^{-15} p^3 - 3.8013e^{-10} p^2 + 17.956e^{-5} p + 96.859 . \tag{4}$$

The momentum conservation governing equation solves the flow field of the entire fluid domain, ie the velocity field. The gravity term and the external stimulus are added to the equation. The specific expressions are as follows:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v}\vec{v}) = -\nabla p + \nabla\left[\mu\left(\nabla \vec{v} + \nabla \vec{v}^T \right) \right] + \rho g - \rho(\dot{\boldsymbol{\omega}} \times \boldsymbol{r} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \boldsymbol{r} + 2\boldsymbol{\omega} \times \boldsymbol{V}) \tag{5}$$

The energy conservation equation for the computational domain is as follows：

$$\frac{\partial}{\partial t}(\rho E) + \nabla\left(\vec{v}(\rho E + p) \right) = \nabla(\lambda \nabla T) + S_h \tag{6}$$

The energy source is equal to the total mass transferred by the latent heat of vaporization:

$$S_h = S_m h_{fg} \tag{7}$$

3.2 Boundary Condition

The ship is shaken by waves at sea and converted into external excitation on the wall of the tank. The simple harmonic function is expressed as the following functional relationship:

$$y = A \sin\left(\frac{2\pi}{T} t \right) \tag{8}$$

$$v = y' = A \frac{2\pi}{T} \cos\left(\frac{2\pi}{T} t \right) \tag{9}$$

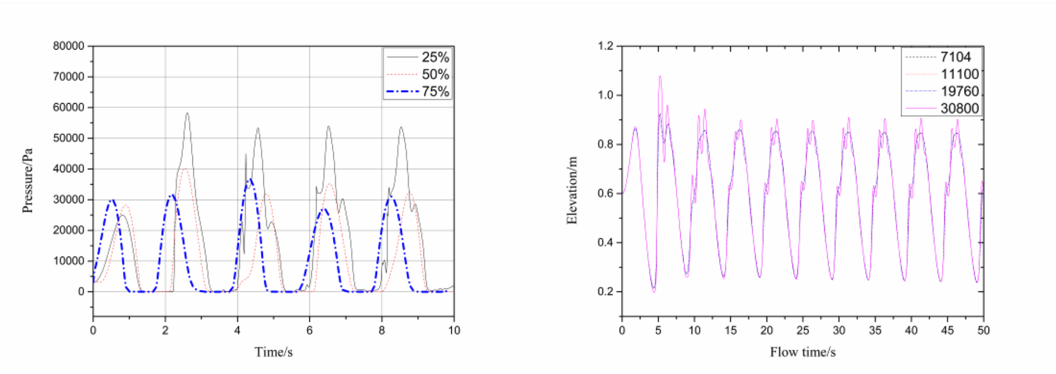
$$\mathrm{a} = y'' = -\mathrm{A} \frac{4\pi^2}{T^2} \sin\left(\frac{2\pi}{\mathrm{T}} \mathrm{t} \right) \tag{10}$$

A is the amplitude of sloshing, T is the period, and t is the sloshing time. The center of rotation is at the center of the tank and the axis of rotation is the Z axis. The slosh excitation equation is imported into the model through a custom function interface.

The heating condition of the surrounding wall is the third type of thermal boundary condition, namely the Newton cooling formula:

$$\lambda \frac{\partial \mathrm{T}}{\partial \mathrm{x}} = \mathrm{h}\left(T_a - T_w \right) \tag{11}$$

4. Model Verification



(a) Impact pressure with time at different liquid levels (b) Liquid level elevation with time in different grids

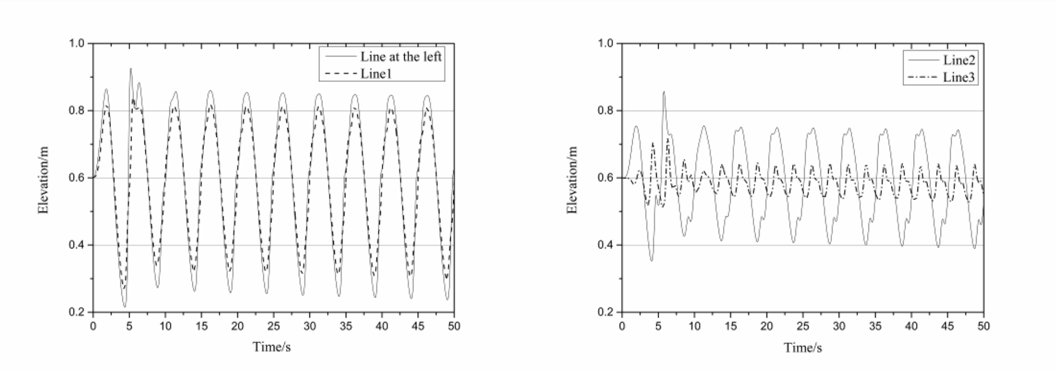
Fig. 2. Impact pressure calculation results and experimental comparison and grid independence verification

The numerical algorithm used in this paper is used to calculate the case in the literature. Fig. 2 (a) Calculates the change of pressure at the detection point with time. It can be seen that the liquid level is measured under the condition of 25% and the literature experiment [4]. The change trend of the pressure value is about the same, but the fluctuation of the pressure peak is not exactly the same. The liquid level is at 50%. The pressure value of the numerical solution is basically the same as the experimental value change process, but slightly at each peak point. Some deviations, so the numerical algorithm in this experiment is correct and feasible, and the next step of research can be continued.

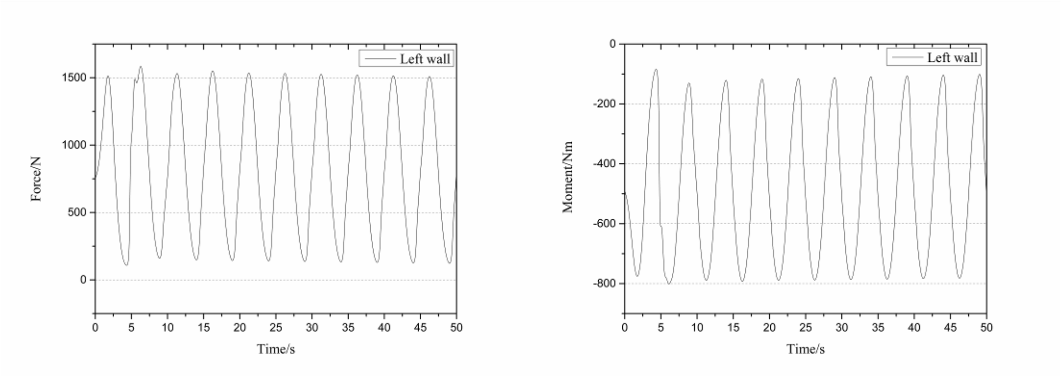
In order to test the sensitivity of the grid, Figure 2 (b) calculates the rise of the liquid level of the left wall in the four sets of grids 7104, 11100, 19760 and 30800 with time, as shown in the figure, with the network As the number of grids increases, the lift height shows a change of about 0.1 m at the peak. The up and down changes will be larger, and there will be a small tortuous change during the ascent, but the overall trend is basically consistent. The number of grids does not have a large impact on the calculated physical quantities, and the grid independence check is verified. In order to save computation time and improve computational efficiency, the number of grids used in this paper is 7104.

5. Results and Discussions

5.1 Sloshing dynamics characteristics



(a) Liquid level elevation at the left wall and test line L1 (b) Liquid level elevation at detection line L2 and detection line L3



(c) The force at the left wall (d) The amount of torque applied to the left wall

Fig. 3 The relationship between the lift height of LNG liquid level on different vertical planes and the force and moment on the left wall surface with time

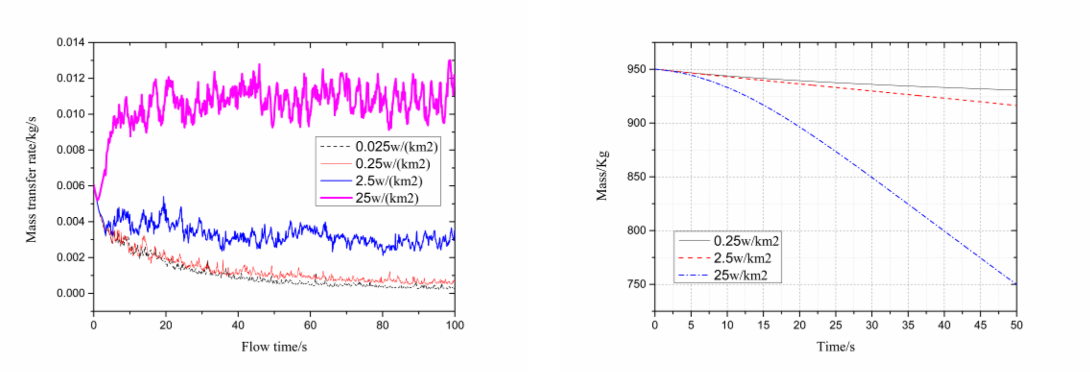
Under the action of sloshing in the presence of gas space in the LNG storage tank, the internal interface between the cryogenic liquid and the gas phase zone induces continuous fluctuations. The VOF algorithm is used to calculate and capture the shape of the liquid surface. In order to analyze the variation law of the fluctuation, the experiment is arranged. From the left to the right four vertical detection planes, the four liquid level elevation curves of Figures 3(a) and (b) are obtained. Curve 3 is the detection result of the middle vertical plane. According to the symmetry of the model, only the fluctuation of the left half is calculated. Compared with the last 40s, the shape of the fluctuation curve at 0-10s changes drastically, and the peak value of the liquid level rise on the left wall surface reaches 0.9m. During the late 40s sloshing, the liquid surface fluctuates up and down in a certain range, and the equilibrium position is the initial liquid level, that is, 0.6m. The reason is that when the sloshing of the storage tank starts, the liquid is in a static state, there is no kinetic energy, and the liquid has a certain inertia. When all the liquids of the LNG absorb the external sloshing energy, the liquid periodically fluctuates regularly and periodically. From the elevation curve of the liquid surface, it can be found that the closer to the middle, the smaller the fluctuation peak of the liquid, and the less external sloshing energy absorbed.

Fig. 3(c) and (d) respectively detect the forces and moments received on the inner wall surface of the LNG storage tank. From this result, it can be found that the sloshing within 10 s will give the inner wall a peak force of 1700 N and peak torque - At 100 Nm, the corresponding liquid is subjected to a reaction force, causing the liquid level to rise to a maximum value, which can also be observed according to the above liquid level elevation curve. Due to the external excitation, the LNG in the tank suddenly changes from stationary to motion, and there is inertia. After 10s stabilization, the force and moment measured on the left wall of the LNG storage tank and the liquid level move back and forth at the initial horizontal line position have a similar cyclical variation.

Based on the above analysis, the sloshing process of liquid in the LNG storage tank changes dynamically with time. The actual process is far more complicated and varied than in this case. Through the investigation and research in this paper, some practical engineering problems can be provided. Valuable theoretical guidance.

5.2 Influence of external leakage heat on phase variables of sloshing LNG storage tank

Marine LNG fuel storage tanks are subject to external heat intrusion due to operational errors, poor sea conditions or damage to bulkhead materials, and are considered to be subject to continuous sloshing of LNG storage tanks. For the convenience of research, it is assumed that different amounts of leakage heat from the outside are transmitted to the LNG, which is approximately expressed as a boundary condition of the bulkhead in different convective heat transfer coefficients. The amplitude of the sloshing of the storage tank is 6° , the period is 5s, and the liquid filling amount is 25%. As can be seen from Fig. 4, the numerical simulation shows the LNG under the conditions of 0.025w/km2, 0.25w/km2, 2.5w/km2 and 25w/km2. The mass flow rate of vaporization into BOG changes with time. After 20s, the amount of evaporation will tend to stabilize. When the convective heat transfer coefficient is 2.5w/km2 or less, the evaporation of LNG is first reduced and then stabilized within a certain range. When the heat transfer coefficient is 25w/km2, the evaporation will increase first and then remain unchanged. The phase variables will fluctuate up and down within a certain interval, which is caused by the instability of the sloshing effect. Since the heat transfer from the gas phase to the liquid phase is much smaller than the wall directly contacting the liquid, when the heat transfer coefficient is large enough (eg, 25 w/km 2), the phase variable will have a rising process. It can also be seen from the figure that the initial value of the phase variables of the four operating conditions is approximately 0.0055 kg/s. This is because LNG is affected by static pressure. The liquid pressure on the surface is small, and the saturation temperature is small. The liquid pressure at the bottom corresponds to a large saturation temperature. The initial temperature of the entire calculation domain is set to the surface saturation temperature of 111.6k. The LNG surface is first reached. At the phase change point, the bottom liquid also has a certain degree of subcooling. When the ship is swaying from side to side at sea, the liquid level in the LNG fuel storage tank will also move and change, and the internal liquid will force convection, which accelerates the heat exchange inside the liquid.



(a) LNG evaporation flow rate (b) LNG liquid quality reduction

Fig. 4 Variation of evaporation and mass with time under different convective heat transfer coefficients

The external heat leakage has a great influence on the quality of the cryogenic liquid in the LNG storage tank. As shown in (b) of Figure 4, the larger the external heat leakage, the larger the convective heat transfer coefficient, the LNG cryogenic liquid, as shown in (b) of Figure 4. The more the mass is degraded, the LNG liquid in the storage tank drops from 950 Kg to 750 Kg under the condition of 25 w/km 2 . The decline in LNG quality is relatively large, which is significantly greater than the reduction in evaporation. It is due to the Boussinesq hypothesis that LNG will decrease in mass after heat absorption, and the change in physical properties will cause the density of LNG to decrease significantly more than the evaporation.

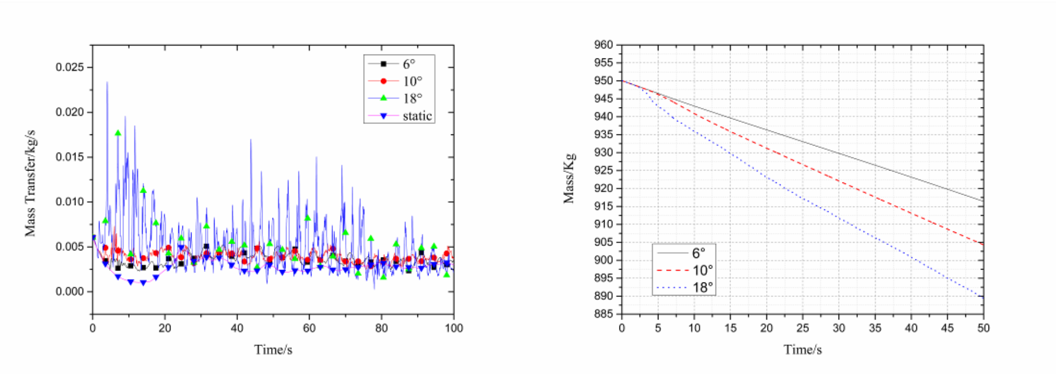
5.3 Influence of different sloshing amplitudes of marine vessels on phase variables of LNG storage tanks

In the dual-fuel ship, the LNG fuel-powered storage tank is taken as the research object, and the sloshing effect and the temperature difference effect are considered. Under the action of the two-effect coupling, the change of the phase-change rate and the flow condition in the LNG storage tank are explored.

When the ship is sailing on the sea, it will be affected by waves of different amplitudes. The LNG fuel power storage tank will also cause sloshing of different amplitudes. It is found from Fig. 5 that the phase change of LNG into BOG in the fuel storage tank is relatively stable when it is stationary. , roughly around 0.003kg / s. In the case of sloshing, as the amplitude increases, the phase change rate of LNG will also increase, and the fluctuation is also very intense and unstable. Between 0 and 25 s, as the amplitude increases, the phase variable will increase, and the difference between the different amplitudes will be more obvious. With the increase of time, the curve of the phase variable will become more and more consistent at 0.003kg/s. Fluctuating up and down.

When the ship is stationary, the LNG fuel storage tank is exposed to external heat leakage, and heat conduction and natural convection are dominant. After the ship has sloshing effect, there is not only heat conduction and natural convection, but also forced convection. Under this mixing effect, the sensible heat in the internal liquid will accelerate the absorption, and the heat of the internal fluid is more uniform. The phase change of the LNG in the storage tank will exhibit unstable characteristics as the sloshing strength rises, especially in the early stage. Between 25s, when the external heat is completely transferred to the latent heat of vaporization of LNG, the gasification amount of LNG is gradually stabilized.

As can be seen from Fig. 5, the greater the sloshing of the ship, the greater the amount of evaporation in the LNG storage tank, and the more obvious the degradation of the quality of the LNG. When the sloshing amplitude is 18° , the temperature of the LNG is reduced from 954 Kg to 894 Kg. 60Kg is less, the average evaporation rate is 1.2Kg/s, and when the amplitude is 10° , the average evaporation rate is 0.82Kg/s, and when the amplitude is 6° , the average evaporation rate is 0.68Kg/s. It can also be seen from (a) that the amplitude of the sloshing will enhance the heat transfer effect of the LNG liquid and increase the evaporation rate.



(a) LNG evaporation flow rate (b) LNG liquid quality reduction

Fig. 5. Evaporation and mass change with time at different amplitudes

5.4 Influence of the height of the sloshing LNG storage tank on the phase change loss

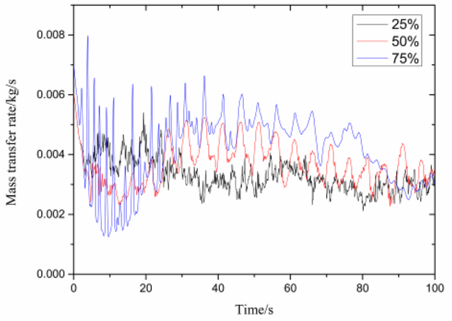


Fig. 6. Comparison of mass transfer rate under different liquid filling rates

Considering that under actual working conditions, LNG fuel will be consumed at any time, and there will be different liquid carrying capacity in the storage tank. Three different liquid volume fractions are set in this paper, which are 25%, 50% and 75% respectively. Under the condition that the external sloshing excitation condition and heat dissipation condition are unchanged, as shown in Fig. 6 , the mass transfer flow curve of LNG will have certain fluctuation under different LNG volume fraction, and the amplitude is about 0.001kg/s. Different volumes of LNG have different masses, and the volume is more natural. Therefore, the inertia of LNG is also large. In the fuel storage tank containing 75% of LNG liquid, the inertia is maximum under the same external excitation. It can be seen that under the 75% liquid filling rate, the overall volatility of the mass transfer rate with time is the largest, between 0 and 40 s, first decreasing and then increasing, and decreasing from 50 to 100 s. After 100s, under the three liquid filling rates, the mass transfer rate curves overlap more and tend to be consistent.

At the beginning, the more liquid filling in the storage compartment, the larger the contact area of the inner wall surface of the liquid, and the more the leakage heat of the liquid contacting the wall surface, the larger the mass transfer rate. The LNG in the storage tank is filled with more liquid, and it is subjected to more static pressure. The subcooling degree of the bottom LNG liquid is also large, and the sensible heat contained therein is also more. In the process of releasing sensible heat, the liquid filling amount is 75%. The working condition has a maximum drop of 0.007kg/s. When LNG evaporates and absorbs latent heat, the extent of the evaporation flow rate rises more obviously.

5.5 Impact of different frequency sloshing on the quality of LNG

When the ship is sailing at sea, the LNG storage tank will change irregularly with the speed of the ship, and the change of the sloshing frequency will be the change of the sloshing cycle. As shown in Fig. 7, the curves of liquid LNG quality over time at four different sloshing frequencies are mainly calculated. The greater the sloshing frequency, the more the quality of the LNG liquid inside the tank drops. When the frequency is 0.24, the drop is 42 kg, and the average reduction rate is 0.84 kg/s. The main reason is that the LNG liquid absorbs external heat leakage, its density decreases, and the physical properties change. Part of the reason is that the phase change of LNG endotherm occurs. Compared with the decrease of density, the evaporation of LNG is only very large. a small proportion. Because the frequency of sloshing is larger, the period is smaller. In the same time, the number of times the tank swings back and forth is more, and the convection effect of the liquid is more prominent, which makes the LNG heat more uniform, thus enhancing the heat exchange between the LNG liquid and the external environment. Eventually, the quality of LNG will be greatly reduced. From the numerical experiments, we can know that in the actual design and management of small LNG storage tanks, comprehensive vibration isolation and anti-wave measures should be taken to prevent the physical properties of LNG liquid from fluctuating drastically and affect the subsequent LNG combustion process.

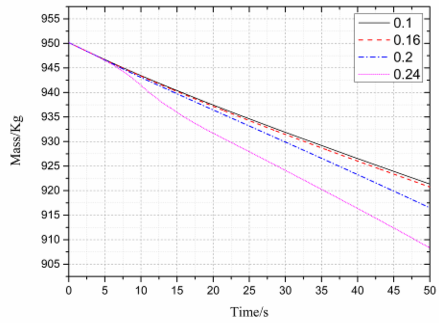


Fig. 7. Quality change with time at different sloshing frequencies

6. Conclusion

1) This paper uses the commercial CFD software FLUENT numerical simulation to simulate the transient effect of LNG power ship fuel storage tank during sloshing for 100s, and obtains the mass flow rate of LNG phase into BOG with different convective heat transfer coefficient, liquid filling amount and the variation of amplitude. In the 100s transient process, the final evaporation of LNG is very low. Because this case mainly considers the influence of static pressure in the liquid phase, there is a certain degree of subcooling at the bottom of the liquid phase, and the amount of cold contained is relatively high. The sloshing effect of the upper storage tank accelerates the mixing of the cold energy at the bottom to the top, so that the evaporation of LNG is reduced, and even the condensation of BOG in the gas phase zone occurs.

2) This case assumes that the pressure change in the gas phase zone is neglected. The main consideration is the static pressure generated by the liquid in the liquid phase under its own gravity.

In actual management, since the LNG power fuel storage tank is running the fuel at all times, the pressure in the gas phase zone is basically kept stable by the pneumatic valve control in most of the time periods. In the future, the influence of dynamic changes in the gas phase region may also be the main research variable.

3) Because of the high degree of nonlinearity and randomness of sloshing, the LNG phase transition rate in the tank is unstable, and different amplitude fluctuations occur. In general, the phase change rate will eventually have a certain steady trend. Through the analysis and research of this phenomenon, it provides a theoretical reference for the operation and maintenance of LNG fuel storage tanks under the actual conditions of marine vessels.

Acknowledgements

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