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Finite Element Analysis on the Thermal Stress of LNG Carriers' Tanks

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The liquefied natural gas (LNG) is one of energies for modern carriers, but the usage of LNG has certain risks. Therefore, the thermal stress of LNG carriers' tanks is analyzed in order to ensure the safety of ships. The temperature field and the thermal stress distribution of ships full of goods are calculated by the finite element method. The results show that the local inhomogeneous temperature field is produced in ships' tanks under the huge temperature difference.When invar membrane wall of the main screen damaged, the temperature distribution of tank cannot meet the requirements of LNG evaporation rate less than 0.15%.

1. Introduction

Natural gas is a kind of energy with high cleanliness and calorific values, which is usually used as energies for modern carriers. But its temperature must be kept under -163 ℃ in order to ensure the safety of natural gas, otherwise it is easy to occur cracking and bending, producing great safety hidden troubles. In order to ensure the safety, it is very important to analyze the thermal stress of LNG carriers' tanks.

This paper investigates and researches the enclosure system of LNG carriers' tanks, obtains the advantages and disadvantages, and conducts the comprehensive analysis combined with the development. In this paper, the finite element heat transfer analysis and calculation are carried out with the example of 147000 m3 thin film LNG carriers. At the same time, Ansys is used to mode tanks and conduct the theoretical analysis and research. For the heat transfer theory,

The finite element method of the temperature field and thermal stress is discussed in detail, and finally the temperature and thermal stress distribution of tanks are obtained when the 147000 m3 thin film LNG carriers are fully loaded.

2. Literature review

According to the relevant norms and guiding principles, the three-carbin finite element model of a 28000m3LNG ship is established. Lu et al. pointed out that, according to the force characteristics of the medium and small LNG ship, the external load and the internal load could be loaded, and the finite element strength analysis was carried out (Lu et al., 2018). According to the calculation results of the finite element model, the deformation and the stress state of the hull structure under various working conditions were understood. Miana and so on analyzed the calculation conditions of the main functions and the structure was reasonably improved (Miana et al., 2016).

Ahn et al. stated that high strength steel should not be used in the bottom, side and deck of the cargo tank of the membrane type LNG carrier. It is mainly to improve the longitudinal strength of the hull and reduce the longitudinal bending deformation of the hull, thus reducing and limiting the additional stress caused by the main longitudinal bending of the hull, and finally prolonging the service life of the ship and improving the fatigue resistance of ships (Ahn et al., 2017). Two kinds of common LNG transport ships were compared and analyzed. The advantages of the deck area layout of the film type LNG transport ship were pointed out. The upper deck area is wider and more flat, and the pipeline equipment is easy to be arranged. Taking a 220 thousand cubic meter of thin film liquefied natural gas ship as the research object, Crocker and others compared and analyzed the similarities and differences between LR, DNV and ABS classification society in structural specification design. They also are carefully discussed the differences of the structural corrosion

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thickness and local strength calculation formula of different specifications. Finally, the local support of the film type LNG transport ship was given. The feasibility of the proposed method was verified by numerical calculation (Crocker et al., 2016). Taking a 6400m3LNG ship as an example, Perl and Steiner evaluated the total strength and strength of the whole ship by direct calculation. It was found that the results of strength calculation were not very different without considering the dynamic load brought by the ship movement or only considering the dynamic load caused by the sway and the longitudinal roll. The calculated results of the whole ship model would be significantly larger than that of the cabin model (Perl and Steiner, 2016).

Based on the 1000m3LNG transport ship, Liu et al. discussed the problems of the selection of the model, the size of the ship and the airworthiness of the Yangtze River on the basis of the in-depth study of the operating costs and the conditions for the navigation of the Yangtze River. The finite element modeling of the saddle and the nearby hull structure of a 6400 cubic meter LNG ship was carried out by using ANSYS software. For different working conditions, load superposition method was applied to load the required specifications, and the stress distribution results were obtained. The calculation results were analyzed, the dangerous conditions and dangerous parts were found, and the structural improvement measures were given in view of the stress distribution, which provided some reference for the structural strength analysis and structure design of similar saddle structures (Liu et al., 2017). Shin evaluated the total strength of the 160 thousand cubic meter LNG ship by the direct calculation method, and the MSC.PATRAN software was used to establish the LNG ship's whole ship finite element. The key calculation techniques were discussed in detail, and the corresponding technical ways and solutions were given. The accuracy of the direct calculation method of the whole ship was high, which could describe the real stress state of the navigation conditions. It could also reasonably evaluate the deformation and stress state of the whole ship in the wave (Shin, 2015).

Ship optimization design combines modern intelligence, mathematical programming and computational mechanics, computer science and other engineering sciences together. It is an important direction in the field of modern structure optimization design. The idea of structural optimization design, such as the theory of equal strength beam and truss theory, was put forward in the long term engineering practice and at the end of nineteenth Century. After more than 100 years of development, the application scope of structural optimization design has been expanded gradually from the field of aeronautics and astronautics to automobiles, ships, machinery, bridges, and even more extensive water conservancy and construction fields.

At present, the structure optimization of the ship is mainly based on the theory of material mechanics and structural mechanics. Lee et al. demonstrated the different structural forms with the corresponding finite element strength calculation and structural optimization software. According to the related structure form, the corresponding mathematical model was set up, the optimized objective function, the constraint condition and the design variable were determined, and several different optimization methods were studied. Therefore, the optimal design method of structure optimization was chosen to achieve the lightest weight or the most cost saving requirement of the structure. The existing optimization design studies mainly focused on ship structure and offshore platform structure. The main object of optimization was the horizontal cross section bulkhead structure optimization, longitudinal component optimization design and cargo compartment structure optimization design (Lee et al., 2018). Because there are many difficulties in the optimization design of the ship's section structure, there are many difficulties in the design variables and the complex constraints, especially in the structural optimization design, which contains a lot of very high nonlinear constraints. The domestic scholars achieved many achievements for the establishment of an effective optimization method for the middle section design.

To sum up, in the above research work, natural gas ship is mainly used as the main equipment for the long distance transportation. It has low temperature and much load in the liquid cargo hold. It is well known for the design requirements of material performance, structure design, thermal insulation structure and reliability. The dynamic load and sloshing load on the cargo tank during the operation of the ship will affect the safe operation of the ship's liquid cargo hold, and it is a problem to set up the structure of the fluid shock to prevent the fluid impact. Therefore, based on the above research status, the stress and strain distribution diagram of the fluid shock structure in the liquid cargo tank is focused on, and the stress evaluation on the simulation results is carried out according to the theoretical calculation results. On the basis of fully analyzing the simulation results and combining the structural characteristics of the impact structure of the original control fluid, the optimization items and optimization objectives are determined. In other words, the weight of the structure is reduced and the stress distribution of the structure is optimized, so as to reduce the cost of manufacturing and improve the safety and reliability of the structure.

3. Analysis Method

3.1 Calculation of Temperature Fields and Distribution of LNG Tanks

Generally, in the process of heat transfer, the temperature within the object changes with the space position and time. Thus, each temperature T is a function of position coordinates (x, y, z) and time t:

$$T = T(x, y, z, t) \tag{1}$$

The distribution of temperature in the time field and the space field at any time is called the temperature field. The same temperature values are connected to form an isothermal surface of this moment as shown in Figure 1. The tangential temperature along the isothermal surface is invariant, while others will change. The tangential temperature along the normal direction of vertical isothermal surface changes greatly. The vector of the maximum rate of temperature increase becomes a temperature gradient.

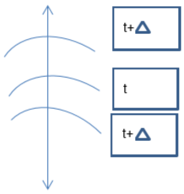

Figure 1: Vectorial diagram of temperature gradient and heat flux density

As shown in equation 1, if the temperature changes over time, the temperature field is unstable. If not, it is called a stable temperature field or a constant temperature field. The temperature in the stable temperature field is just a function of position, that is:

$$T = T(x, y, z) \tag{2}$$

While in a flat area, the mathematic expression of the stable temperature field is:

$$T = (x, y), \left(\frac{\partial T}{\partial \mathrm{t}} = 0, \frac{\partial T}{\partial \mathrm{z}} = 0 \right) \tag{3}$$

It is assumed that the temperature gradient ΔT of p in the temperature field will get warming $\frac{\partial T}{\partial n}$ along the normal direction of the isothermal surface. When the unit vector is

$$\mathrm{n}_0 , \quad \Delta T = \mathrm{n}_0 \frac{\partial T}{\partial \mathrm{n}} \tag{4}$$

The change rate of temperature along this direction is:

$$\left. \begin{aligned} \frac{\partial T}{\partial \mathrm{x}} &= \frac{\partial T}{\partial \mathrm{n}} \cos(\mathrm{n}, \ \mathrm{x}) \\ \frac{\partial T}{\partial \mathrm{y}} &= \frac{\partial T}{\partial \mathrm{n}} \cos(\mathrm{n}, \ \mathrm{y}) \\ \frac{\partial T}{\partial T} &= \frac{\partial T}{\partial \mathrm{n}} \cos(\mathrm{n}, \ \mathrm{z}) \end{aligned} \right\} \tag{5}$$

The amount of heat per unit area in unit time is called heat flux density (or heat flux). The maximum heat flux density vector of this point will get cooling along the normal direction of the isothermal surface:

$$\mathrm{q} = -\mathrm{n}_0 \frac{\mathrm{d}Q}{\mathrm{dt}} \frac{1}{S} \tag{6}$$

According to the law of heat transfer, the heat flux density is proportional to the temperature gradient in the opposite direction

$$q = -\lambda \Delta T \tag{7}$$

where λ is the coefficient of thermal conductivity in $\lfloor kj/(m\,h\,c) \rfloor$.

$$\lambda = \frac{dQ}{dt} \Big/ \frac{\partial T \frac{1}{S}}{\partial n} \tag{8}$$

$$q = \lambda \frac{\partial T}{\partial n} \tag{9}$$

$$q_x = -\lambda \frac{\partial T}{\partial x}, q_y = -\lambda \frac{\partial T}{\partial y}, q_z - \lambda \frac{\partial T}{\partial z} \tag{10}$$

Equation 8 is achieved in combination with equations 4, 6 and 7. The heat flux q is calculated Equation 9 based on the above equations. The values on x, y and z axes are Equation 10, respectively. Because axes are arbitrarily chosen, the above expression is that the value of heat flux on any axis equals the coefficient of thermal conductivity times the temperature decline rate in that direction. The daily evaporation rate is obtained as shown in Table 1.

Table 1: Dayevaporation rate

workingcondition	1	2
Heat exchange	24659	42820
Diurnal evaporation rate	0.0949	0.1547

3.2 Finite Element Analysis of Temperature Stress in Thin Film LNG Tankers

Firstly, the load of finite element calculation model can be divided into the bending moment is directly loaded to the independent point, the shear load to the transverse bulkhead, the external sea pressure to the hull plate, internal loads to the infrabasal plates and inner sides.
Meanwhile, according to hull girder theory, bending momenta are forced to load on both ends of the model. Bending moments reach the target values in the midship section of the model, and the shear loads reach the target values in the transverse bulkhead of the model, keeping the load balance of the whole model. Based on the common specification JTP of double hull oil tankers' structure, the above-mentioned forces can be calculated as the following steps.
(1) Unit Conversion
Shenll57 and solid70 are converted into shell63 and solid45, and material properties and real constants, such as the stiffness coefficient and the poisson ratio, are set.
(2) Apply Load
The previous calculated temperature load is applied as the body load to solve the calculation in the model.
(3) Boundary Conditions
Boundary conditions should fully reflect the influence of other unmodeled parts, the stress of components, and the corresponding stress due to the previous finite element analysis, such as the multi-point constraint unit is used on the end surface, the bending moment is applied on the rigid point of the end surface, and symmetrical boundary conditions are loaded in the central lateral plane.
(4) Analytical Results

4. Results and Analysis

When invar membrane wall of the main screen intact or damaged, the temperature load as a body load is added into the model. It can be seen that the temperature stress is not large when tanks loaded with cryogenic liquids. Thus, the temperature loads have a little influence on the hull structure strength and the total displacement. But for some components, such as the floor and the deck, there is a great influence as shown in Table 2.

Table 2: Stress of typical components

workingcondition	floor	Bottomplate	Deckplate	Decklongitudinalanalysis	Transversebulkheadwall	Sideanalysisandanalysis
1	172.2	114.8	134.1	95.7	92.6	153.1
2	153.7	102.4	119.5	85.4	90.2	136.6

Figure 2 shows the temperature stress curve of the deck along the costal plate under the working condition 2. It can be seen from the figure, the temperature stress of the deck near the transverse bulkhead is larger, and then that in the midship section decreases gradually. However, the strong stress needs to be further processed.

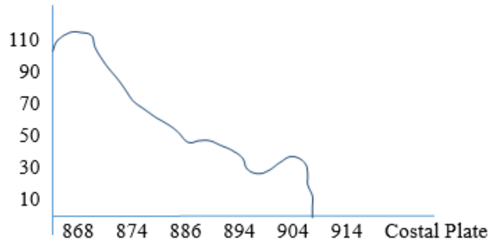

Figure 2: Temperature stress curve

Form the calculated temperature stress distribution, it can be seen that the stress difference of each unit is small under these two working conditions, which is because the temperature gradient caused by the temperature stress is not large. But the temperature has a great influence on the stress of the components near the transverse bulkhead, which is due to the large rigidity of the transverse bulkhead restricts the free transform of the surrounding structures, resulting in a large transverse stress. For the components far from the transverse bulkhead which can be transformed freely in vertical directions, the stress is small mainly generated by the temperature gradient.

In order to compare the proportion of thermal stress in the strength analysis, this paper conducts the strength analysis on structures under full load. The boundary conditions of the calculation model for the structural stress analysis are rules and regulations of CCS. The ANSYS command is used to compile ASEL,S,LOC,X,0; NSLA,S,1; NSEL,A,,,l; CP,11,UX,ALL; CP,12,UZ,ALL; CP,13,ROTY,ALL; CP,14,ROTZ,ALL; D,1,UX,0; D,1,UY,0; D,l,UZ,0; D,1,ROTX,0; D,1,ROTZ,0; ASEL,S,LOC,X,36*0.74; NSLA,S,1; NSEL,A,,,2; CP,20,UY,ALL; CP,21,UZ,ALL; CP,22,ROTX,ALL; CP,23,ROTZ,ALL; D,2,UY,OD,2,UZ,0; D,2,ROTX,0; D,2,ROTZ,0; ASEL,S,Loc,Y,0; D,ALL,UY,0; D,ALL,ROTX,0; D,ALL,ROTZ,0. Then the stress is calculated by the wave and cargo loads on the basis of the oil ship standards as shown in Tables 3 and 4.

Table 3: Working condition1

Working condition	floor			Bottom plate			deck		
	Thermal stress	Structural stress	Synthetic stress	Thermal stress	Structural stress	Synthetic stress	Thermal stress	Structural stress	Synthetic stress
	172.2	58.1	220.8	114.8	90.8	82.4	134.1	98.1	223.2

Table 4: Working condition2

Working condition	floor			Bottom plate			deck		
	Thermal stress	Structural stress	Synthetic stress	Thermal stress	Structural stress	Synthetic stress	Thermal stress	Structural stress	Synthetic stress
	153.7	58.1	218.2	102.4	90.8	80.4	119.5	98.1	215.3

5. Conclusion

This article takes 147000 m3 thin film LNG carriers as research objects, as well as uses large-scale general finite element analysis software ANSYS to mold 1/4 tanks under full load and to calculate the temperature field distribution and the thermal stress when invar membrane wall of the main screen intact or damaged. Two typical enclosure systems of LNG carriers' tanks are studied in terms of structural materials and adiabatic structures. The finite element calculation method of the temperature field and stress is summed up with thermal knowledge.

The solution method for the coefficient of thermal conductivity in the thermal insulation blanket is a feature of this paper. It simplifies the application of the coefficient of thermal conductivity of each insulation material, but there is no big difference in results. This paper analyzes and researches the calculated temperature field and thermal stress under two working conditions from the actual situation of LNG carriers under full load, as well as discusses the resulting local hull strength problems, which have certain reference value for the design and construction of thin film LNG carriers.

Under certain conditions, a large number of calculated data are obtained by the finite element calculation according to the actual model, as well as the temperature field and stress of thin film LNG carriers are analyzed. The analytical results show that when the LNG carriers are loaded, its hull temperature distribution has an important influence on the safety and efficiency. The stress caused by the temperature to the structural strength cannot be ignored.

There are still many areas that need to be improved in future research. This is mainly manifested in the following aspects:

(1) Foreign advanced tank construction and insulation technology should be continued to track and comprehensively analyzed in detail based on the actual situation in China.

(2) The more meticulous and accurate finite element analysis of LNG carriers is carried out to further improve the study on temperature and stress distributions of tanks. With various environmental and working conditions, the finite element method is used to calculate temperature and stress distributions of tanks. The strength of 147000 m3 thin film LNG carriers is obtained in combination with the structural stress.

(3) When the temperature field and stress is calculated, there are certain assumed conditions. However, how to compute the temperature and stress of thin film LNG carriers in the actual situation needs further research.

(4) The calculated results are compared with the data obtained from domestic and foreign experiments to verify the feasibility and shortcomings of this method.

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Reference

Ahn J., Choi Y., Jo C., 2017, Design of a prismatic pressure vessel with internal X-beam structures for application in ships. Ships and Offshore Structures, 12(6), 781-792, DOI: 10.1080/17445302.2016.1247487

Crocker L.E., Duncan B.C., Broughton W.R., 2016, Assessment of test methods for a cryogenic liquid containment system. International Journal of Adhesion and Adhesives, 70, 126-136, DOI: 10.1016/j.ijadhadh.2016.06.004

Lee J., Jo C., Chang D., 2018, New methodology for estimating the minimum design vapor pressure of prismatic pressure vessel for on-ship application. Ocean Engineering, 158, 367-377, DOI: 10.1016/j.oceaneng.2018.04.008

Liu D., Tang W., Wang J., 2017, Hybrid RANS/LES simulation of sloshing flow in a rectangular tank with and without baffles. Ships and Offshore Structures, 12(8), 1005-1015, DOI: 10.1080/17445302.2017.1301341

Lu H., Ma G., Li X., 2018, Stress Analysis of LNG Storage Tank Outlet Pipes and Flanges. Energies, 11(4), 877, DOI: 10.3390/en11040877

Miana M., Legorburo R., Díez D., 2016, Calculation of boil-off rate of liquefied natural gas in mark III tanks of ship carriers by numerical analysis. Applied Thermal Engineering, 93, 279-296, DOI: 10.1016/j.applthermaleng.2015.09.112

Perl M., Steiner M., 2016, 3-d stress intensity factors due to full autofrettage for inner radial or coplanar crack arrays and ring cracks in a spherical pressure vesse. Procedia Structural Integrity, 2, 3625-3646, DOI: 10.1016/j.prostr.2016.06.452

Shin S.H., 2015, A Study on Simplified Analysis for the Initial Tank Design of Spherical Type LNG Carriers. Journal of the Society of Naval Architects of Korea, 52(2), 125-134, DOI: 10.3744/snak.2015.52.2.125