Thermal Design of LNG Cabin on Sea Transports

Rong LI, Xuda SHAN, Juyong ZHANG
School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou, China, 310018

ABSTRACT: The LNG (Liquefied Natural Gas) cabin is a key component in the maritime transport of -163℃ LNG. The cryo-insulation performance of cabin directly affects the security of LNG transport greatly. Based on a 10000m^3 LNG ship, two structural schemes of the LNG cabin are certain, which include their materials, supports and parameters. One is two single cylinder with 5000 m^3, the other is a vertical cylinder with 10000 m^3. With the safety requirements of cryopreservation of -163℃ LNG, it calculates the heat leakage of two schemes. Lastly, the temperature field distributions of two types of LNG cabins with full load are simulated by 3d mathematic models by finite element software.
KEYWORD: LNG; cargo tank; heat-insulating layer; thermal design

1 INTRODUCTION

Nowadays, as a product of natural gas, LNG (Liquefied Natural Gas) mainly relies on import over sea in most of countries. Since the boiling point of LNG is -163℃ under standard pressure, it needs maintain the ultra-low temperature during its transportation. The LNG cabin is used to load the -163℃ LNG, which must be protected strictly from ocean shipping environment. Therefore, the cryo-insulation performance of cabin directly affects the security of LNG transport greatly. And the thermal design of cabin becomes its design point. Based on a 10000m^3 LNG ship, a structural & thermal design of its LNG cabin is put out. In order to ensure its security of cabin, under thermal design requirements, the thermal performance of cabin must be checked strictly.

2 LNG CABIN

Film type cabin and independent ball type cabin are two main kinds of LNG cabin used in LNG ship. There are ripple structures on inner wall of film type cabin usually, and the internal structure of film type cabin is often simple with 98% volume utilization rate. The cabin structure consists of two shielding structures: the main shielding structure and the secondary shielding structure. Besides, it needs a metal thin film additionally provided insulation structure in the cabin structure to ensure its heat insulation. While the independent type cabin and the hull is independent of each other. The weight of its cabin is undertakes by itself. Therefore, there is no deformation or stress concentration on the hull itself.

In order to ensure the safety and efficiency of the LNG ship during its transportation, there are many strict requirements on its cabin in the design of LNG ship. At present the common types of LNG ship are as follows. And the cabin is usually made of 9% nickel thick plate or low temperature resistant aluminum alloy, with polyurethane foam. There is also a secondary screen wall structure outside of cabin, to prevent LNG leakage.

With tiny heat, -163℃ LNG will generate vaporization, and its volume rapidly increases more than 600 times at the same time. The vaporized gas mixed with air easily explodes. In the process of transportation, the security of LNG dependents on thermal insulation performance of LNG cabin.

3 STRUCTURE DESIGN OF LNG CABIN

In the first scheme, 10000m^3 LNG is divided into two cabins with 5000m^3 volume. Since LNG ship is 120m long and 20m wide, the size of LNG cabin is restricted by the size of ship, as shown in Table 1.

Table. 1 Parameters of 5000m^3 single cylinder cabin

Diameter of cabin	Length of cabin	Volume of cabin	Vertical gap	Length of ship	Width of ship
15m	33.5m	5036.365m^3	5m	120m	20m

Nowadays, the cabin is usually made of low temperature aluminum-killed steel, 9% nickel steel, and Cr-Ni austenitic. Since stress of aluminum alloy is the minimum among three materials, it is not suitable for cabin for its large thickness wall. The parameters of the other two materials are shown in Table 2.

Table.2 Comparison of two materials

Material	Allowable stress	Minimum design pressure	Weight of cabin
9% nickel steel	213Mpa	3.5 Mpa	211T
Cr-Ni austenitic	150 Mpa	2.74 Mpa	292T

With low hardness, moderate intensity, plasticity, toughness, good mechanical properties, good welding performance, Cr-Ni austenitic is more suitable for LNG cabin. To prevent heat leakage, LNG cabin is arranged on the other surface with 300mm polystyrene insulation materials, through special adhesive adhesion. To protect layer polyethylene foam, 0.5mm galvanized steel sheet is on the most outer layer.

In the second scheme, vertical cylindrical cabin structure includes outer cabin and inner cabin. A cylinder cabin with a bottom plate consist the inner cabin, with 9% nickel steel. A vault, cylinder cabin and floor board consist the outer cabin, with carbon steel for it is not contact LNG directly. The structure and parameters of 10000m^3 vertical cylinder cabin are shown in Table 3.

Table.3 Parameters of vertical cylinder cabin

Item	Filler	Geometric volume	Effective volume	Evaporation rate	Material	Diameter	Height
Inner tank	LNG	11200m^3	10404 m^3	0.046%	9% nickel steel	24m	15 m
Outer tank	Nitrogen, pearly sane	--	--	--	Q345R	28 m	17 m

Insulation structure of vertical cylinder cabin includes top cabin, bulkhead and bilge. The top cabin is made of low carbon steel, concrete and 9% nickel steel. To prevent thermal deformation, 9% nickel steel and expanded perlites consist of bulkheads with a layer of elastic mat inside. There is a ring bottom around the insulation beam in bilge, for bearing the weight of cabin and LNG, contacting heat transfer and hull. Perlite concrete is used as thermal insulation in vertical cylinder cabin, while foam glass brick is used in bilge heart part. The parameters of insulation materials in vertical cylinder cabin are shown in Table 4.

Table.4 Parameters of insulation materials in vertical cylinder cabin

Item	Vault		Ceiling		Inner cabin		Bottom			
Material	Low carbon steel	Concrete	9% nickel steel	Glass fiber	9% nickel steel	Expaned perlite	Foam glass	Sand	9% nickel steel	Concrete
Thermal concuctivity W (m K)	11.6	0.70	10.2	0.038	10.2	0.05	0.049	0.269	10.2	0.7
Thickness mm	6.8	350	5	1200	6	1000	430	300	16.7	100

4 SUPPORTING STRUCTURE AND HEAT LEAKAGE

Single cylinder cabin is horizontal, supported by two bearings. One of support is mobile, for avoiding gravity by bending and additional stress. The support is a double-layer compression wood filled with epoxy mortar pad for insulation. Assuming environment temperature is 40℃, heat leakage of single cylinder cabin is calculated from formula (1).

$$Q = qA = \alpha(T_2 - T_1)A \quad (1)$$

Here, Q-heat transfer of cabin unit area, W/m^2; α-total heat transfer coefficient of cabin, W/（m^2·K）; T_1-temperature of inner cabin, K; T_2-temperature of outer cabin, K; A- insulation area of cabin wall, m^2. The total heat leakage is 100.584KW, meeting thermal requirements of LNG cabin.

The evaporation rate is calculated from formula (2).

$$\alpha = \frac{Q\times 24}{\gamma V\rho} \times 100\% \tag{2}$$

Here, γ-evaporation potential of LNG, 142kJ/kg; V-volume of cabin, m^3; ρ-density of LNG, 425kg/m^3;Q-total heat, W. The result is 0.000794%, which meets design needs.

For vertical cylindrical cabin, there is an annular pillar structure without cooling tube in pillar space to support cabin. Its heat leakage of cabin bottom is calculated by formula (3).

$$\varphi_b = \frac{T_b - T}{R_b} \tag{3}$$

Here, T_b-average temperature of cabin bottom, 275K; T-temperature of system, 112K; R_b-thermal resistance of cabin bottom, 0.275K/W. The result is 5.564KW. Its heat leakage of cabin side wall is calculated by formula (4).

$$\varphi_c = \frac{T_\infty - T_{cx}}{R_c} \tag{4}$$

Here, T_∞-ambient temperature, K; T_{cx}-temperature of annular space between inner wall and outer wall of cabin, K; R_c-thermal resistance of inner layer of cabin, K/W. The result is 0.901KW. Its heat leakage of cabin top is calculated by formula (5).

$$\varphi_{r,d} = \frac{\sigma_b (T_\infty^4 - T_{dx}^4)}{R_{r,d}} \tag{5}$$

Here, $R_{r,d}$-thermal radiation resistance of top cabin, K/W; T_∞-ambient temperature, K; T_{dx}-temperature of space between cabin wall and top cabin, K; σ_b-Stefsn Boltzmann constant, 5.67×10-8W/(M^2·K$^{4)}$. The result is 27.78KW. Total heat leakage of vertical cylindrical cabin is: $\varphi=\varphi_b+\varphi_c+\varphi_{r,d}$=34.245KW, which less than the design requirements of 250KW.

The evaporation rate of vertical cylindrical cabin is calculated from formula (6).

$$\alpha = \frac{Q\times 24}{\gamma V\rho} \times 100\% \tag{6}$$

Here, γ-evaporation potential of LNG, 142kJ/kg; V-volume of cabin, m^3; ρ-density of LNG, 425kg/m^3; Q-total heat, W. The result is 0.00012%, which meets design needs.

5 THERMAL SIMULATION OF CABIN INSULATION STRUCTURE

With the help of “Ansys” finite element software, the numerical simulation of LNG two types of cabin are. And the effectiveness is also verified. In view of LNG cabins are axial symmetry structures, the numerical models of two cabins are simplified during thermal analysis.

Single cylinder cabin is 33.5m long and in 7.5m radius, with 3 layers of insulation material. The thickness and properties of insulation materials are shown in Table 5. According to design requirements, temperature of LNG in cabin is -163℃, temperature of environment is 40℃, and the convection coefficient is 12.5 W/m^2·℃. Its thermal simulation result is shown in Figure 1.

Table.5 Thickness and parameters of single cylinder cabin insulation materials

Item	Thermal conductivity/W (m K)	Thickness/mm
Cr-Ni austenitic	16	30
Polystyrene foam	0.116	300
Zinc plate	116	0.5

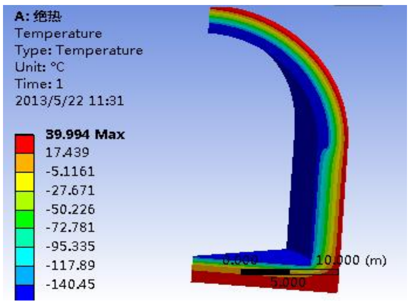

Figure 1 Simulation result of single cylinder cabin

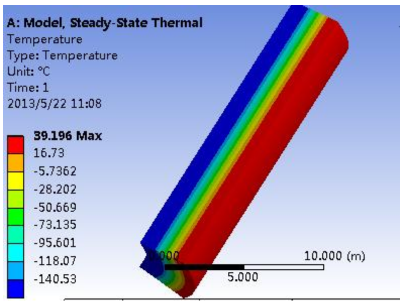

Figure. 2 Simulation result of vertical cylinder cabin

For the second scheme, insulation material of vertical cylindrical cabin is relatively complex. The thickness and properties of its insulating material layer are shown in table 4. Similarly, temperature of LNG in cabin is -163℃, temperature of environment is 40℃, and the convection coefficient is 12.5 $W/m^2 \cdot ℃$. Its thermal simulation result is shown in Figure 2.

As shown above, temperature distributions of two types of cabin are basically meet the design requirements. But two schemes of cabin are different in application process still, which are shown in Table 6.

Table.6 Two scheme comparison of LNG cabins

Item	Single cylinder cabin	Vertical cylinder cabin
Volume/m^3	5000×2	10000
Heat leakage/KJ	50.292	34.245
Daily evaporation rate/%	0.046	0.0012
Safety	Normal	High
Cost of manufacturing	Cheap	Expensive
Difficulty of technology	Normal	Complex
Support structure	Sliding bearing and fixed bearing	Group of stainless steel tube
Consumption of insulation material	Less	More

Comprehensive consideration of safety, scheme of vertical cylindrical cabin is adopted lastly.

6 SUMMARY

This paper mainly analyzes two types of $10000m^3$ cabin on LNG ship. Then two typical cabins are studied from their insulation structure, supporting structure, heat leakage and daily evaporation rate. At last, scheme of vertical cylindrical cabin is adopted as final scheme.

ACKNOWLEDGEMENTS

This research was financially supported by the Project supported by the Zhejiang Provincial Natural Science Foundation of China (No. LQ13E060004). This work was supported by Zhejiang Open Foundation of the Most Important Subjects (No. 201205).

REFERENCES

[1] Chen Ruiquan, Lu Sheng. Study on C-type LNG tank design. *Ship engineering*. 2013, 1:11-13, 69.

[2] Pei Yiqun, Lu Sheng, Liu Wenhua. Structural design and research of type-C independent tank on small scale LNG ship. *Journal of ship design*. 2012, 2:28-34.

[3] China Classification Society. *Rules for materials and welding 2009*. Beijing. China Communications Press. 2009.

[4] The editorial board of Pressure vessel technology series. *Pressure vessel design knowledge*. Beijing. Chemical Indusrry press. 2005.

[5] Ship carrying liquefied gases in bulk and equipment specification. Dalian. *China Classification Society*. 2006.

[6] Manual calculation of pressure vessel GB150,151. Beijing. *China pressure vessel standardization committee*. 2001.