Frontiers in Power and Energy Systems (2024)
Clausius Scientific Press, Canada
DOI: 10.23977/fpes.2024.030112
ISSN 2516-2926 Vol. 3 Num. 1

A Review of the Temperature Field Research of C-type Liquid Tanks on Small and Medium-sized LNG Ships

Jinhua Qian[1,a,*], Xuhui Jiang[1,b], Yitong Liu[2,c]

[1]*School of Ocean Engineering, Jiangsu Ocean University, Lianyungang, 222005, China*
[2]*Makarov College of Marine Engineering, Jiangsu Ocean University, Lianyungang, 222005 China*
[a]*qianyidaoshi@163.com,* [b]*1479297966@ qq.com,* [c]*2072754972@ qq.com*
[*]*Corresponding author*

Keywords: Natural gas, Liquid tank, Temperature field, Review

Abstract: Natural gas is a recognized green fuel that is colorless, odorless, non-toxic, and non-corrosive. As people around the world pay more and more attention to the atmosphere and ecological environment, humans use natural gas more frequently. This study aims to summarize the existing research results of some LNG ship C-type liquid tanks by studying the problems encountered in the storage and shipping of liquid tanks. Studies have shown that scholars have studied many aspects of liquid tank temperature field calculations at this stage, but they mainly use FLUENT software to calculate and study in the form of steady-state temperature fields. The article concludes that in the future, non-steady-state temperature fields can be used to improve the accuracy of calculations, and the combined effects of multiple coupled fields can be considered. At the same time, different software such as STAR CCM can be used to compare results to make the research results more convincing.

1. Introduction

As people around the world pay more and more attention to the atmosphere and ecological environment, humans are paying more and more attention to the direction of developing green fuels. Natural gas is a colorless, odorless, non-toxic, and non-corrosive green fuel recognized worldwide. Its main component is methane, and it also includes a certain amount of ethane, propane and heavy hydrocarbons, as well as a small amount of nitrogen, oxygen, carbon dioxide and sulfide. It is usually stored and transported in a liquid state. In ship shipping, LNG carriers can be roughly divided into three types according to the type of liquid tank: type A, type B and type C. Type A is a membrane liquid tank, type B is a spherical vertical liquid tank, and type C is an independent liquid tank. Type C independent liquid tanks are usually semi-cold and semi-pressurized, with high structural strength, no primary or secondary shielding structure on the hull, and a relatively simple structure. They are suitable for small and medium-sized ship transportation, so the market for independent liquid tanks is relatively broad [1]. For example, one of the LNG ships is shown in Figure 1. Type C independent liquid tanks can be further divided into single-body tanks, double-ear tanks, and three-body tanks according to their different structural forms. In the current situation of global economic downturn, C-type double-ear tanks have become the main force in liquefied natural gas transportation among LNG transport ships because of their greatly reduced and shortened manufacturing process and production cycle compared to A-type membrane liquid tanks, B-type spherical vertical liquid tanks and C-type three-body tanks, and their superior transportation volume compared to independent liquid tanks.

At the same time, because LNG carriers are different from conventional ships, the cargo they carry is -164℃ liquefied natural gas. During operation, the temperature difference between the LNG in the liquid cargo tank and the external atmospheric environment can be as high as 200℃ or more. The temperature field distribution of the liquid cargo system maintenance system and its hull structure is very complex. In the structural calculation and analysis of LNG ships, the analysis of temperature field and its thermal stress plays a decisive role. Therefore, it is necessary to study the temperature field of C-type LNG carrier liquid tanks.

Figure 1: Ocean Oil 301

2. Research Status at Home and Abroad

In the heat transfer process of LNG tankers, heat conduction, heat convection and heat radiation are accompanied. Based on the development of heat transfer, scholars have studied computational heat transfer and conducted a lot of research on practical heat transfer problems.

Yang[2] et al., based on the characteristics of LNG tanks and combined with heat transfer theory, derived the calculation formula for temperature field distribution, studied the heat flux density and temperature distribution of the tank from radial and axial directions, and established a set of numerical methods for finite element analysis of low-temperature tank temperature field.

Zhu Xuexi[3], based on the analysis of heat transfer theory, derived the heat leakage calculation model of the bottom, wall and top of the LNG tank, and took a large LNG tank as the research object to conduct numerical simulation of temperature field and pressure field. The research results show that the bottom of the tank is the main area of heat leakage. This conclusion provides an important reference for the design of the insulation area of LNG tanks in engineering.

Henkes[4] et al. simulated the natural convection problem under the vertical side wall heating of a two-dimensional square cavity, and compared the calculation results of the K-epsilon model and the low Reynolds number turbulence model.

Ma Honglin [5] applied the ADI method to the numerical simulation of natural convection in a closed square cavity and studied the changes in the cavity streamline field and temperature field under high Rayleigh numbers.

Li Min [6] conducted a static temperature field analysis on LNG tanks or cargo tanks and indirectly studied the prediction of evaporation parameters by calculating the heat leakage;

Wang Wuchang, Shao Xiaogeng [7-8] and others used finite element and CFD methods to explore the factors affecting the evaporation rate of LNG on the basis of certain simplification and analyzed the influence of pressure and loading on evaporation.

Li Boran, Li Yang [9-10] and others considered sloshing on the basis of static simulation to realize the evaporation simulation of LNG in motion. The stratification and tumbling of LNG were also explained in the form of cloud maps to predict the evaporation state of LNG under complex working conditions.

In addition, many domestic and foreign scholars have conducted in-depth research on liquid tank heat transfer, sloshing, evaporation analysis, etc., which will not be elaborated here.

3. Challenges Faced

There are many challenges in studying the temperature field of C-type liquid tanks of LNG (liquefied natural gas) ships. These challenges mainly involve the temperature distribution inside and outside the liquid tank, thermal management, safety, and storage and transportation characteristics of LNG. The following are some of the main challenges:

3.1. Uneven Temperature Distribution

Temperature gradient in the tank: In the C-type tank of an LNG carrier, LNG is usually kept at a low temperature of around -162 ℃. Due to the shape and structure of the tank, the temperature distribution of the liquid and gas may be uneven. For example, different temperature gradients may appear in the top and bottom areas of the tank. The heat exchange between the liquid and vapor layers is very complex and requires precise simulation and control to ensure stable temperature in the tank.

Temperature fluctation: The navigation environment of LNG carriers includes frequent temperature changes, which may cause fluctuations in the temperature in the tank. Such fluctuations not only affect the storage stability of LNG, but may also affect the durability and structural integrity of the tank material.

3.2. Heat Flow and Heat Transfer

Thermal intrusion problem: The C-type tank of an LNG carrier usually adopts an inner and outer double-layer structure, and the insulation layer design is complex. Despite good insulation materials, heat from the external environment (such as solar radiation, seawater temperature, etc.) may penetrate into the tank, causing the temperature to rise. Especially during long-term navigation, the accumulation of external heat may cause uneven increase in the tank temperature, which in turn affects the evaporation and storage safety of LNG.

Uneven heat exchange: The temperature of natural gas in LNG tanks is affected by external conditions, liquid level changes, and internal gas flow. How to accurately predict and control the heat exchange process in the tank and maintain the thermal balance between liquid and gas is a difficult problem in temperature field research.

3.3. Structural Materials and Thermal Expansion

Thermal expansion of materials: The low temperature of liquefied natural gas will cause great thermal expansion and contraction of the structural materials of the tank (such as aluminum alloy, stainless steel, etc.). These changes may cause deformation of the material and affect the sealing and structural strength of the tank. How to design a reasonable structure to cope with the impact of such temperature changes on the material is a challenge in the design and research of C-type tanks.

Thermal failure of insulation layer: C-type tanks usually use efficient insulation materials to reduce heat loss, but under long-term low temperature conditions, the insulation materials may age or degrade, resulting in reduced heat conduction efficiency and making temperature management more difficult.

3.4. Temperature Monitoring and Control

The accuracy of real-time monitoring system: Accurate monitoring of the temperature in the tank is crucial to ensure the safety of LNG ships. How to establish a high-precision, real-time temperature sensor network and ensure the accuracy and stability of the data is still a technical problem. Small fluctuations in temperature changes may affect the evaporation rate of LNG, thereby changing the pressure inside the tank and affecting the navigation safety of the ship.

Accuracy of thermodynamic models: The study of temperature field usually relies on thermodynamic models to simulate the heat transfer and heat flow behavior in the liquid tank. However, due to the complex structure inside the liquid tank, dynamic liquid level changes, gas-liquid phase change and other factors, the existing thermodynamic models are often difficult to fully and accurately reflect the changes in the temperature field.

3.5. Evaporation and Replenishment of Liquefied Natural Gas

Thermal management of evaporated gas: During the storage of liquefied natural gas, part of the LNG will evaporate due to the increase in temperature and produce vapor. In order to maintain the stability and safety of the liquid tank, these vapors must be handled. The control of vapor pressure, the cooling of evaporated gas, and the pressure management of the liquid tank are all important factors that need to be considered in the study of temperature field.

Efficiency of cooling system: The design of the cooling system on LNG ships needs to deal with the changes in the temperature inside the liquid tank, especially the temperature fluctuations that may be faced during transportation. The efficiency and stability of the cooling system directly affect the balance of the temperature field and the storage safety of LNG.

3.6. Safety Issues

Safety hazards caused by excessive temperature: If the temperature inside the liquid tank is too high, LNG will produce too much gas, which may cause the pressure inside the tank to increase, and even cause structural rupture or leakage. In order to avoid safety accidents caused by excessive temperature, the temperature field needs to be precisely controlled and managed.

Relationship between temperature and liquid tank material: The material used for the liquid tank must be able to maintain good strength and toughness at extremely low temperatures, and at the same time be able to withstand the stress caused by temperature fluctuations. Too high or too low temperature may affect the physical properties of the material and even cause the material to crack.

3.7. Dynamic Operating Conditions

Temperature changes during navigation: LNG ships face changes in external environmental temperature during navigation, such as seawater temperature, weather changes and other factors. These factors will affect the dynamic balance of temperature inside and outside the tank. It is a challenging task to study how to maintain temperature stability under these dynamic conditions.

The coupling effect of liquid level and temperature: The LNG level in the tank will change with the tilt, fluctuation and evaporation during transportation, and the temperature distribution of the liquid and gas layers will also change accordingly. This coupling effect of liquid level and temperature increases the complexity of temperature field research. The problems described above are shown in Table 1:

Table 1: Challenges faced summary

	Challenges	Specific issues1	Specific issues2
3.1	Uneven temperature distribution	Temperature gradient in the tank	Temperature fluctuations
3.2	Heat flow and heat transfer	Thermal Intrusion Problem	Uneven heat exchange
3.3	Structural materials and thermal expansion	Thermal expansion of materials	Thermal failure of insulation
3.4	Temperature monitoring and control	Real-time monitoring system accuracy	Accuracy of thermodynamic models
3.5	Evaporation and replenishment of liquefied natural gas	Thermal management of boil-off gas	Efficiency of cooling system
3.6	Safety issues	Safety hazards caused by excessive temperature	Relationship between temperature and tank material
3.7	Dynamic operating conditions	Temperature changes during voyage	.Coupling effect of liquid level and temperature

4. Summary and Outlook

This paper first explains the necessity of studying the temperature field of LNG tankers based on reality. Then, the current research status of LNG tankers at home and abroad is summarized. Furthermore, the difficulties in the current research on the temperature field of tankers are sorted out. Finally, the full text is summarized to provide some research directions and ideas for future scholars.

In the future research process, in terms of numerical simulation: the non-steady-state temperature field can be used to improve the calculation accuracy, considering the joint effect of multiple coupling fields, and the algorithm can be compiled through the UDF function of the calculation and analysis software fluent. At the same time, different software such as STAR CCM are used to compare the results to make the simulation results more convincing. In terms of thermal insulation materials: exploring more efficient thermal insulation materials can improve the thermal management ability of the tank and reduce the impact of external heat on the tank. In terms of temperature monitoring: develop more intelligent temperature monitoring systems and control algorithms to achieve real-time monitoring and dynamic adjustment of tank temperature to ensure the safety of LNG throughout the transportation process.

In summary, the study of the temperature field of the C-type liquid tank of an LNG ship faces many challenges. It requires the comprehensive application of knowledge from multiple disciplines such as thermodynamics, materials science, and fluid mechanics to solve related problems through theoretical research, experimental verification, and technological innovation.

References

[1] Chen Hong, Mao Liuliu, Tao Fang. Calculation and finite element analysis of independent liquid tank structure of liquefied natural gas carrier[J]. Mechanical Manufacturing, 2018, 56(08):43-46+53.

[2] Yang J. H., Yang G. S. The Temperature Field Research for Large LNG Cryogenic Storage Tank Wall[J]. Applied Mechanics and Materials. 2014, 3590(668-669).

[3] Zhu Xuexi. Analysis and simulation of heat leakage of large LNG storage tanks[D]. Chengdu: Southwest Petroleum University, 2012.

[4] Henkes R., Vandervlugt F. F., Hoogendoorn C. J. Natural L-Convection Flow in A Square Cavity Calculated with Low-Reynolds-Number Turbulence Models[J]. International Journal of Heat and Mass Transfer. 1991, 34(2): 377-388.

[5] Ma Honglin. Numerical simulation of laminar and turbulent natural convection in closed cavity with high Rayleigh number (Ra)[D]. Wuhan: Huazhong University of Science and Technology, 2004.
[6] Li Min. Analysis of temperature and stress fields of C-type independent liquid cargo tanks of small and medium-sized LNG ships[D]. South China University of Technology, 2013.
[7] Wang Wuchang, Li Yuxing, Sun Fafeng, et al. Analysis of factors affecting pressure and evaporation rate in large LNG storage tanks[J]. Natural Gas Industry, 2010(7):87-92, 137-138.
[8] Shao Xiaogeng. Research on evaporation rate of 1.5 m3 independent C-type LNG storage tanks[D]. Dalian: Dalian University of Technology, 2015.
[9] Li Boran. Numerical simulation of tumbling and stratification of LNG cargo tanks under sloshing conditions[D]. Harbin Institute of Technology, 2016.
[10] Li Yang. Numerical analysis of stratified rollover of LNG storage tanks[D]. Xi'an Shiyou University, 2017.