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Research on tumbling of LNG storage tank

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Abstract

With the large-scale import and application of LNG in my country, the number of LNG receiving stations continues to increase, so the demand for LNG tanks, which are an important part of LNG storage in receiving stations, is also increasing. This paper firstly introduces the advantages of LNG (liquefied natural gas), combined with the stratified rollover problem encountered in the current storage and transportation of LNG storage tanks. This paper introduces the research background and research status of LNG stratified tumbling and summarizes the previous research results of scholars. Finally, according to the research trend of LNG storage tank layered tumbling, suggestions and prospects for future research directions of storage tanks are given to promote the development of LNG storage tank research.

Keywords

LNG storage tank, liquefied natural gas, stratified tumbling.

1. Introduction

Natural gas is becoming an increasingly important energy source. Over the past few decades, global natural gas consumption has grown by 28%, and natural gas accounts for nearly 24% of global primary energy demand. As an important part of the natural gas industry, the liquefied natural gas (LNG) industry is experiencing a stage of rapid development. As of the end of 2020, global LNG imports reached 356.1 million tons, an increase of 1.4 million tons or 4% over the previous year. In 2020, the capacity utilization rate of global LNG liquefaction units will be 74.6%. As of February 2021, 139 Mtpa of liquefaction units are under construction or approved globally, and 8.9 Mtpa of liquefaction units are expected to be commissioned in 2021 (World LNG Report 2021).

Since my country is a country with the largest population in the world and consumes a huge amount of natural gas, my country has 68.9 million tons of natural gas imports in 2020, accounting for 19.3% of the market share, an increase of nearly 2% compared with 2019. In 2020, China's natural gas production was 188.85 billion cubic meters, a year-on-year increase of 15.23 billion cubic meters. The statistics of China's natural gas production from 2015 to 2020 are shown in Table 1; the average monthly natural gas production in China in 2020 was 15.74 billion cubic meters, a year-on-year increase. 1.27 billion cubic meters, the monthly average production of natural gas in China from 2015 to 2020 is shown in Figure 2. From January to February 2020, China's natural gas production was 31.41 billion cubic meters, an increase of 2.73 billion cubic meters compared to the same period in 2019; from March to December, China's natural gas production reached its highest value in December, at 18.71 billion cubic meters; The lowest value was reached in August at 14.21 billion cubic meters.

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Table 1 Statistical table of natural gas production in China from 2015 to 2020

years	2015	2016	2017	2018	2019	2020
Natural gas production/billion cubic meters	1334.8	1368.3	1474.2	1610.2	1736.2	1888.5

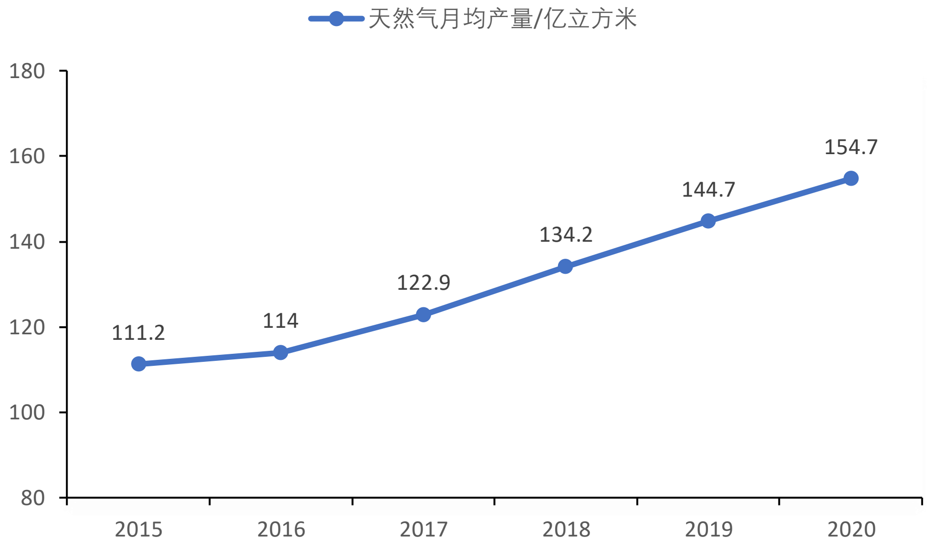

Figure 2 Statistical chart of monthly average natural gas production in China from 2015 to 2020

Under the background of the huge demand for natural gas in my country, the long-distance transportation of natural gas has the characteristics of high cost and low safety, while liquefied natural gas is small in size and light in weight, and it can save a lot of risks by transporting natural gas in the form of liquefied natural gas (LNG). In addition, the volume of the same amount of natural gas in the liquid state is only 1/625 of that in the gas state, so LNG is mostly used for long-distance and large-scale transportation of natural gas. In addition, with the high volatility of natural gas demand in large cities and industries in terms of time and consumption, LNG emergency peak shaving stations have been highly valued in recent years to meet urban seasonal peak shaving, monthly peak shaving, and even daily peak shaving or hourly shaving Peak shaving requirements. The liquefied storage tank is the main storage form of the peak shaving station. Compared with the coastal receiving station, its loading and unloading method has the characteristics of higher frequency of use and greater fluctuation of loading and unloading volume, so the working condition is more severe. Therefore, because of the application requirements of this liquefied storage tank, in recent years, scholars and experts in my country have focused on the establishment of the LNG storage tank tumbling process model, the reasons for the formation of stratification and tumbling, and how to prevent stratification and tumbling. In other respects, it is committed to ensuring the storage safety of LNG storage tanks.

2. Convection phenomenon in the vertical closed cavity

Heat convection refers to the heat transfer process caused by the relative displacement between parts of the fluid caused by the macroscopic motion of the fluid, and the mixing of cold and hot fluids with each other[1]. This paper discusses the stratified tumbling process of LNG in the storage tank, which is a special thermal convection phenomenon. The temperature difference between the hot and cold fluids causes the density difference between the fluids to

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generate a flow called natural convection. The air near the surface of the radiator is heated and flows upward. Forced convection is a phenomenon in which the fluid flows due to the pressure difference generated by the external force exerted by construction machinery, such as condensers, electric fans, etc[2]. Natural convection is a flow driven by buoyancy and density differences caused by differences in fluid temperature or concentration [3]. Differences in fluid density or chemical composition can lead to differences in fluid density. Temperature differences are the more common cause of natural convection. For example, when there is a temperature difference between the fluid and its nearby solid boundary, The temperature of the fluid in the solid wall increases or decreases, which in turn creates a density difference between the fluids near the solid wall and leads to the appearance of natural convection[4]. Depending on the space in which the fluid is located, natural convection has inflow and outflow. Natural convection in a larger space is less affected by the outside world and is called outflow, sometimes called free convection. If the fluid is in a small closed cavity, the movement of natural convection is limited by space, and such natural convection is called internal flow. Under the action of gravity, the difference in fluid density in the sealed space is the main cause of fluid flow. One of the objects of CFD and numerical heat transfer research is the convective heat transfer in the sealed space. The natural convection caused by temperature difference can be divided into vertical temperature difference driving or horizontal temperature difference driving. The natural convection driven by the vertical temperature difference (which can be generated by bottom heating or top cooling or simultaneous loading of two thermal boundary conditions) is the so-called Rayleigh-Bénard convection[5], or RBC for short. The convection inside the LNG storage tank studied in this paper is the Rayleigh-Bénard convection, that is, the internal flow RBC problem.

3. Delamination and tumbling phenomena

LNG is a multi-component mixture, and its physical parameters are related to the content of each component. The main component of LNG is methane, usually including ethane, propane, nitrogen, carbon dioxide, etc. Referring to "Liquefied Natural Gas Technical Manual" [6] and "Liquefied Natural Gas (LNG) Application and Safety" [7], through the calculation formula of physical parameters, it can be obtained that when the temperature is -162℃and the absolute pressure is 0.6 MPa, the methane content is 90% of LNG-related physical parameters are shown in Table 2.

Table 2 LNG physical parameters

Physical parameters	Value (unit)
density	431.20kg/m^3
specific enthalpy	-3.35kJ/kg
specific entropy	0.0615kJ/kg·K
Internal energy	-4.68kJ/kg
compression factor	0.0246
Constant pressure specific heat	3.07kJ/kg·K
Thermal Conductivity	0.1896W/m·K
Thermal diffusivity	1.3634e-7 m^2/s
Kinematic viscosity	2.9270e-7m^2/s
dynamic viscosity	1.3265e-4Pa·s

In general, different LNG components have different densities[8,9]. When filling the storage tank with LNG, the original LNG and the newly injected LNG may form a layered structure due to the difference in density and temperature, that is, liquid layers with different densities and temperatures are formed inside the storage tank. There is a temperature difference of about 180℃ between the inside of the storage tank and the outside of the storage tank. The heat in the environment will be transferred to the liquid in the storage tank through the heat conduction on the wall of the storage tank. The natural convection circulation between the liquids makes the interlayer temperature tend to be consistent; the lower layer liquid not only distributes heat evenly through the natural convection circulation between the layers but also exchanges heat and mass with the upper layer liquid through the liquid layer interface. Because the upper layer liquid has static pressure on the lower layer liquid, the lower layer LNG is in a superheated state due to heat absorption, and the density and temperature of the layered liquid eventually tend to balance due to the heat and mass transfer effects between layers. The lower thermal fluid flows along the bulkhead to the upper space, releases the heat accumulated during the overheating period, and generates a large amount of BOG (boil of gas). This liquid flow behavior is called LNG "tumbling".

The direct cause of the tumbling of the LNG storage tank is the appearance of the uneven density field, and the stratification of the LNG directly leads to the tumbling of the storage tank. Therefore, it is necessary to study the stratification phenomenon before studying the tumbling process of the LNG storage tank.

In the world, there have been many accidents of LNG tumbling in storage tanks caused by the stratification of LNG in storage tanks. These rollover accidents not only cause economic losses but also cause great harm to the environment. Therefore, studying the tumbling of LNG is of great significance for the safe storage of LNG storage tanks.

4. Research status of stratification and tumbling of LNG storage tanks

The research on stratified tumbling of LNG storage tanks is research on the flow and phase transition of LNG thermal fluid in the storage tank under the condition of heat leakage from the tank wall and tank bottom. Scholars at home and abroad have done a lot of experimental research on the stratified tumbling process of LNG and summed up many mathematical models related to it. With the improvement of computer computing power, scholars have conducted more extensive numerical simulation research on the stratified tumbling process of LNG.

There are two accidents with relatively detailed reports in history: the LNG tumbling accident that occurred at the La Spezia storage and distribution station in Italy in 1971 and the LNG storage and distribution station accident in the UK in October 1993. Hours later, the pressure in the storage tank suddenly rose, and the safety valve opened, causing 318 m^3 of LNG to be vaporized and emptied. The accident was caused by the stratification caused by filling the heavier new LNG from the bottom during the filling process. ; When the latter accident occurred, the pressure in the storage tank exceeded the design pressure, and the safety valve and the relief valve were opened successively, resulting in about 150 tons of LNG being completely vented. In the previous stage of the two accidents, there were obvious liquid stratification phenomena[10, 11], and two booms after the two accidents set off a new wave of scholars and experts in many fields to study the stratification and tumbling of LNG storage tanks. A breakthrough has been made in the stratification and tumbling of LNG storage tanks, and the tumbling model of LNG storage tanks has also been developed and improved.

4.1. Experimental Study

The research on the layered tumbling of LNG in storage tanks has been theoretically and experimentally studied by many domestic and foreign scholars since the 1970s. phase, Rayleigh number, parameters such as defining the tumbling coefficient, and the characteristics of the pressure change in the gas phase, and based on this, the theoretical model of layered tumbling is summarized. However, due to the limitations of the experimental research site and safety considerations, other fluids are generally used to replace LNG with different densities and temperatures, and stratification experiments are carried out in the experimental container to explore the flow characteristics and influence mechanism of LNG in the process of stratified tumbling.

In 1984, Sugawara[12] from abroad studied a model storage tank with a diameter of 500 mm equipped with an electric heating device and used Freon as the experimental medium to study the tumbling of the LNG storage tank. Muro, Nakand, Graffis Smith, T. Agbabi, Arita, and others used storage tanks of different shapes and sizes, using salt-water, water-sugar, F11-F113, liquid oxygen-liquid nitrogen, and other media to conduct a large number of experiments. Research.

Wang Hairong[13] conducted a layered simulation experiment using brine based on the analysis of the similarity conditions of LNG layers, described the evolution of the layered instability process, and obtained the formation conditions of the layered system, the failure mechanism of the interface, and the cause of the vortex. and predict it. The effects of initial density difference, layer height, and heating conditions on the vortex were also investigated.

Liu Peng[14] established a vertical cylindrical storage tank experimental system and a square visual storage tank experimental system, using electric heating equipment to simulate an external fire, and monitoring the liquefied gas by collecting the temperature at different heights in the storage tank. thermal stratification process. The research results show that when the whole sidewall of the storage tank is heated, the heating rate of the gas phase area is higher than that of the liquid phase area so that the gas-liquid two phases form obvious temperature stratification. When the full sidewall of the storage tank is heated, the lower the filling rate, the faster the internal temperature and pressure rise, the higher the thermal stratification, and the longer it takes to eliminate temperature stratification for the same vertical distance.

4.2. Simulation study

Due to the continuous improvement of computing speed and computing power of computers in the past ten years, software simulation is widely used in various industries. Therefore, more and more experts and scholars use computational fluid dynamics software as a research tool through the method of numerical simulation for the research on the phenomenon of LNG stratification and tumbling. By changing different setting conditions and selecting different numerical models, the LNG stratified tumbling process and its influencing factors can be studied more extensively and accurately.

Yacine Zellouf et al. studied the tumbling of LNG storage tanks under two different conditions, onshore and offshore[15]. When on the shore, the factors affecting the rollover mainly include the initial density difference of LNG, the height of the layer, the volume of the storage tank, and the heat leakage of the storage tank. Under the condition of sloshing at sea, the movement of the liquid changes the mixing mechanism of LNG stratification, so that the mixing is no longer dominated by molecular diffusion, and the dynamic effect caused by the fluid flow in the layer becomes the key factor affecting the mixing of each stratum. Compared with onshore storage, the mixing time of each layer of LNG under sloshing is significantly shortened, and the factors that cause tumbling are also quite different. The dynamic factors caused by sloshing and the energy accumulated in each layer during mixing have a greater impact on tumbling.

To improve the safety of storage tanks and reduce the cost of LNG storage, Kazuo Koyama used CFD technology to simulate the mixing process of LNG storage tanks when they were filled with LNG of different densities[16]. A case study of the filling of a small storage tank shows that factors such as the initial density difference, the initial LNG level height, and the rate of filling can affect the density difference leading to stratification. The larger the initial density difference, the higher the liquid level, and the higher the filling rate, the larger the density difference required to cause tumbling. After the filling is complete, the density difference will remain stable or decrease slowly.

Roh and Son et al. used Fluent software to simulate the natural convection phenomenon in LNG storage tanks and studied the effects of convection coefficient, tank size, and shape on the LNG flow field, temperature field and interface heat transfer rate in the tank[17]. The research shows that the interfacial heat transfer rate determines the rate of BOG generation, and the effect of the heat transfer rate in the liquid phase region on the BOG generation rate is much greater than that in the gas phase region. The heat transfer rate of the interface is linearly related to the heat transfer coefficient of the outside, and the semicircular section of the tank can reduce the heat transfer and thus reduce the generation of BOG.

Bi Haisheng[18] established a two-dimensional mathematical model based on the FLUENT software to simulate the mass transfer and heat transfer process of LNG storage tank stratification and tumbling. layers were studied in depth. The research results show that: the existence of the initial density difference of LNG is the main reason for the occurrence of tumbling. The larger the initial density difference is, the easier the tumbling will occur; The thermal insulation measures of the storage tank can reduce the heat leakage; the initial critical density difference and the tumbling coefficient can be used as effective criteria for the tumbling of the storage tank.

Sun Futao[19] established a tumbling model of a large-scale LNG storage tank and analyzed the influence of LNG layered temperature difference, layered height, heat leakage, and heat leakage position on the tumbling severity. The research results show that when the heat leakage at the bottom is 10 W/m^2 and the temperature difference between the upper and lower layers is greater than 0.2K, tumbling will occur, and the greater the temperature difference, the easier and more severe the tumbling will be. When the heat leakage at the bottom is $10W/m^2$, and the height of the upper and lower layers is closer, the degree of tumbling will be more severe. Whether it is the bottom heat leakage or the sidewall heat leakage, the greater the heat leakage, the more severe the tumbling. When the heat leakage is the same, the tumbling time of the sidewall heat leakage is earlier than that of the bottom heat leakage, but the intensity is smaller than that of the bottom heat leakage.

Bu Yongcheng[20] and others established two-dimensional and three-layer LNG two-dimensional models, used CFD software to simulate the tumbling process of LNG in a $16×104m^3$ storage tank, and analyzed the density and interface velocity of each layer of the three-layered layer. The change of the two-layer and three-layer interface velocity with time is compared.

Li Dongtao[21] solved the LNG stratification and tumbling model with the help of Fluent software and analyzed the simulation results under different working conditions to obtain the influence of factors such as the number of strata, stratification height, and stratification density difference on the tumbling density field velocity of large LNG storage tanks. field effects, and compare the occurrence, severity, and duration of LNG tumbling. The research results show that: LNG tumbling in three layers with the same diameter and density difference occurs earlier, lasts longer, and tumbles more violently; LNG tumbling occurs later and more violently with higher stratification height; The earlier the LNG tumbling occurs, the more intense it is, and the longer it lasts.

5. Summary and Outlook

Theoretical analysis, experimental research, and numerical simulation methods have been applied by domestic and foreign scholars to the research of LNG tumbling and stratification, and many research results have been obtained. However, there are still many problems, such as the interface motion problem and its influence on tumbling, the criterion of the critical point in each stage of the tumbling process, and the influence of pressure and composition on the tumbling evolution process. If these problems in the process of LNG stratification and tumbling can be solved, the mechanism of stratification and tumbling can be improved, and a more accurate tumbling prediction model and effective prediction method can be proposed, providing support for improving measures to prevent LNG stratification and tumbling.

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