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Research Progress on the Mechanism of Liquefied Natural Gas Rolling and Preventive Measures

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ABSTRACT

As a core component in the liquefied natural gas (LNG) storage and transportation process, the operational safety and efficiency of LNG storage tanks are crucial to the stability of the natural gas supply chain. This paper delves into the mechanism of LNG rolling and its influencing factors, proposing a series of preventive measures. The findings provide theoretical references and practical guidance for the safety management and risk prevention of LNG storage tanks.

KEYWORDS

Liquefied Natural Gas, LNG Storage Tank, Stratification, Rolling, Preventive Measures.

1. INTRIDUCTION

Liquefied natural gas (LNG), as an efficient and clean energy source, plays a pivotal role in the global energy market. With the continuous growth of natural gas consumption in China, an increasing number of large-scale LNG storage tanks have been put into operation. The phenomenon of LNG rolling is a critical hidden risk that affects the safe operation of storage tanks. Although many researchers have extensively studied the LNG rolling phenomenon, the complexity of its underlying mechanisms and the numerous influencing factors make the prevention and control of LNG rolling a challenging task. Therefore, it is crucial to deeply explore the fundamental principles of LNG rolling, identify the main influencing factors, and develop effective preventive strategies to ensure the safety of LNG storage facilities.

2. LNG ROLLING PHENOMENON

The LNG rolling phenomenon refers to the rapid mixing of liquid layers with different densities within an LNG storage tank, leading to the sudden generation of a large volume of boil-off gas (BOG) in a short period. Stratification is a prerequisite for the occurrence of rolling. The primary factors causing LNG stratification include the aging of the liquid in the tank, the injection of LNG with differing densities, and thermal stratification within the tank.

2.1. Aging

Aging refers to the process by which the density of LNG changes during prolonged storage in the tank due to the gradual evaporation of lighter components, such as methane. During aging, if the initial nitrogen content in the LNG is relatively high, nitrogen will preferentially evaporate. Over time, the proportion of lighter components decreases, resulting in an increase in LNG density. For LNG with lower nitrogen content, the evaporation of methane similarly leads to a gradual increase in LNG density.

2.2. Injection of LNG with Different Densities

When LNG with differing densities and temperatures is continuously injected into a tank already containing LNG, and if the newly added LNG fails to mix thoroughly with the existing liquid, distinct stratified layers may form. In such cases, the denser liquid settles at the bottom of the tank, while the lighter liquid floats on the upper layers. This stratification occurs due to incomplete mixing caused by density differences between the liquids[2]. For continuously operating receiving terminals, stratification in LNG storage tanks is often attributed to this cause.

2.3. Thermal Stratification

Thermal stratification arises from the uneven distribution of temperature within the tank caused by external heat sources, such as heat leakage through the tank walls or the tank bottom. This uneven temperature distribution creates density differences within the LNG, leading to the formation of stratified layers[3].

3. FACTORS INFLUENCING LNG ROLLING PHENOMENON

The LNG rolling phenomenon in storage tanks may cause structural damage to the tank, leading to leakage or even explosions, which pose severe threats to both personnel and environmental safety.

3.1. Density Difference and Injection Height

For denser heavy fluids, when injected from the top of the storage tank, gravity and density differences promote thorough mixing of the newly injected LNG with the existing liquid in the tank. After settling, the liquid layers distribute more evenly. However, if injected from the bottom of the tank, the liquid will settle at the bottom, and gravity limits the mixing between the liquids, resulting in significant stratification within the tank[6]. For less dense light fluids, when injected from the bottom, buoyancy causes the light fluid to rise naturally, mixing fully with the heavier upper layers. After settling, stratification only forms at the bottom of the tank. In contrast, when injected from the top, buoyancy causes the light fluid to mix with the upper layers without affecting the lower layers, resulting in noticeable stratification after settling.

Therefore, when injecting heavy fluids, using the top inlet can avoid stratification; for light fluids, injecting from the bottom can accelerate mixing, although partial stratification may still form near the tank walls.

3.2. Stratification Height

Under the same tank volume and density difference conditions, the greater the stratification height, the longer the occurrence and duration of LNG rolling, and the greater the maximum speed of the stratification interface. This results in a more intense rolling phenomenon. Conversely, if the stratification position is lower, the duration of rolling will be shorter, and the amount of BOG generated during rolling will be les.

3.3. Nitrogen Content in LNG

The higher the nitrogen content in LNG, the greater the tendency for rolling to occur. This is because nitrogen has a low boiling point, and a higher nitrogen content increases LNG's volatility. During the rolling process, the higher the nitrogen content, the greater the instantaneous volume of BOG generated, which exerts a more significant impact on the tank pressure and destructive force, making the rolling phenomenon more intense[7].

3.4. Initial Density Difference

The density difference is a key factor in LNG rolling. The larger the initial density difference, the shorter the time for LNG rolling to occur, the longer the duration, and the more intense the rolling phenomenon. Wu Song[8] conducted a simulation analysis of LNG storage tanks and proposed a critical density difference model. The study found that the critical density difference for LNG storage tanks with volumes ranging from 5000 m^3 to 160,000 m^3 lies within the following intervals: 6.5-7.2, 6-6.5, 5-5.5, 4.5-5, 4-4.5, 3.8-4, 3.2-3.5, and 3-3.2 kg/m^3. Furthermore, as the diameter of the storage tank increases, the stratified LNG is more susceptible to rolling due to density differences.

3.5. Tank Volume and Filling Rate

The larger the storage tank volume, the more dispersed the liquid layers of LNG, making the flow and mixing processes more complex. This leads to a longer occurrence time for rolling, a shorter duration, and more intense rolling phenomena[9]-[10]. Additionally, the filling rate of the tank also significantly influences LNG rolling. When the filling rate is low, there is more space for liquid flow, which may lead to more intense rolling; when the filling rate is high, the liquid is packed more tightly, increasing flow resistance and potentially suppressing the occurrence of rolling.

3.6. Impact of Environmental Heat Leakage Intensity

The greater the environmental heat leakage intensity around the LNG storage tank, the shorter the occurrence time of rolling. Heat leakage in the tank primarily comes from the sidewalls and bottom. When the leakage intensity from both sources is relatively low, increasing the intensity of either one significantly shortens the time for LNG stratification and rolling to occur. However, as the heat leakage intensity increases, its effect on rolling time diminishes. When both sources of heat leakage have low intensities, increasing either one will notably reduce the rolling time. However, when one source of heat leakage is significantly higher, increasing the other has a lesser effect on rolling time.

4. PREVENTION AND CONTROL OF LNG ROLLING

4.1. LNG Storage Tank Design and Structural Optimization

The design of LNG storage tanks is crucial to their entire lifecycle, making it essential to strictly adhere to current standards and regulations. Currently, several industrially developed countries or regions, including China, have established detailed regulations and standards for the design, construction, and operation of atmospheric pressure LNG storage tanks. The relevant domestic and international standards are listed in Table 1[11].

Table 1 Domestic and International Standards/Regulations for the Design, Construction, and Operation of Large Atmospheric Pressure LNG Storage Tanks

Country/Region	Standard Title	Standard Code
United States	"Design and Construction of Large Welded Low-Pressure Storage Tanks"	API STD 620
	"Liquefied Natural Gas (LNG) Production, Storage, and Shipping Standards"	WPA59A
	"Welded Steel Petroleum Storage Tanks"	API STD 650
China	"Design Code for Vertical Cylindrical Welded Steel Oil Tanks"	GB 50341-2014
	"Design Code for Vertical Cylindrical Welded Steel Petroleum Storage Tanks"	SH 3046-1992
	"Welded Steel Pressure Vessels"	JB/T 4735-1997
European Union	"Design and Construction of On-Site Assembled Vertical Cylindrical Steel Low-Temperature Liquefied Gas Storage Tanks with Operating Temperatures between 0°C and -162°C"	BSEN 1462
United Kingdom	"Design of LNG Equipment and Installation for Land-Based Installations"	BSEN 1473:2016[12]
	"Design and On-Site Construction of Cylindrical, Flat-Bottom, Steel Cold Liquefied Gas Storage Tanks with Operating Temperatures Between 0°C and -162°C"	BSEN 14620-5:2006[13]
Japan	"Guidelines for Liquefied Natural Gas Aboveground Storage Tanks"	JGA 指-108-02
	"Guidelines for Liquefied Natural Gas Aboveground Storage Tanks"	JGA 指-107-02

The American Petroleum Institute standards API 650, API 620, and the British Standard BS EN 14620-2:2006 are widely recognized as the ultimate standards for the design and construction of storage tanks and are extensively applied worldwide. In the design of LNG storage tanks, to effectively prevent stratification and rolling phenomena, the following key considerations must be addressed:

When calculating the insulation performance, the local highest ambient temperature must be thoroughly considered, and efficient thermal insulation materials must be carefully selected to mitigate the impact of environmental heat, thereby reducing the vaporization rate. Typical LNG insulation materials include elastic fiber mats, expanded perlite, polyurethane foam, and foam glass, among others.

The LNG tank surface monitoring system plays a critical role in preventing and controlling rolling phenomena. This system must monitor comprehensively key process parameters such as liquid level, pressure, and density, utilizing devices such as liquid level temperature density meters (LTD), servo liquid level meters, radar liquid level meters, and multi-point average thermometers. Additionally, it must be equipped with a side-tank display instrument and other relevant accessories (such as junction boxes). The system is capable of monitoring LNG state changes within the tank in real time, providing accurate measurement data to operators, and issuing alerts upon detecting abnormal parameters, thereby guaranteeing the safe and stable operation of the tank.

4.2. Operation Control and Management Strategies

Optimization of feed and mixing strategies. When the density of the newly injected LNG exceeds that of the existing LNG in the tank, it should be introduced through the top feed port[14]. Conversely, when the density of the new LNG is lower, the bottom feed port should be employed. Simultaneously, mixing nozzles or porous tubes must be utilized for LNG injection. During this process, it is imperative to ensure that the nozzle is in contact with the liquid surface and that sufficient time is provided for thorough mixing between the liquids[15].

Storage of LNG from different gas sources. To avoid LNG stratification caused by density differences, LNG from different sources or gas fields should be stored separately. This method is suitable for LNG receiving stations with a larger number of tanks, while it is generally not feasible for peak-shaving LNG receiving stations with fewer tanks.

LNG Nitrogen Content Control. For LNG with a higher nitrogen content, it should not be stored in the tank for extended periods and should be discharged as quickly as possible. In general, the nitrogen content (mole fraction) in LNG components should be less than or equal to 5%. The component requirements for LNG are shown in the table.

Table 2 LNG Component Requirements

Component	Content
CH4	>0.75
N2	<0.05
H2O	<0.1×10-6 (v)
CO2	(50~100)×10-6 (v)
COS	<0.1×10-6 (v)
Aromatics	<10×10-6 (v)
C5+	<70 mg/m3
H2S	<3.5 mg/m3
Total Sulfur	<50 mg/m3
Mercury	<0.01 mg/m3

Note: (mol) represents mole fraction.

Layering Elimination and Prevention. To prevent the layering phenomenon in LNG storage tanks and reduce the risk of rollover, measures such as internal circulation and external reliquefaction can be used to achieve liquid-phase homogenization. For example, periodic activation or activation upon detection of layering can effectively promote the mixing of LNG with different densities, maintaining density consistency within the tank. Alternatively, external reliquefaction can be used to reliquefy the gas-liquid mixture inside the tank and return it to the tank, achieving component homogenization and thermodynamic stability.

5. CONCLUSION

Scholars both domestically and internationally have conducted in-depth analyses of the mechanisms and influencing factors of LNG rollover through theoretical analysis and numerical simulations. Based on the rollover generation mechanisms and influencing factors, targeted research on prevention and control has been carried out to develop scientifically effective preventive measures, which are crucial for ensuring the safety of LNG storage tanks. On-site, through optimizing tank design, improving operational management, and implementing real-time monitoring, the occurrence of rollover phenomena can be effectively reduced, ensuring the safe operation and environmental protection of LNG storage tanks.

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