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Calculation and Analysis of Influencing Factors of Daily Evaporation Rate for Large LNG Storage Tank

Zhang Wenhao, Tian Guansan*, Yin Xiao

School of Thermal Engineering, Shandong Jianzhu University, Jinan, China

Email address:
17865312572@163.com (Zhang Wenhao), tgs4170@sdjzu.edu.cn (Tian Guansan), Y686997x@163.com (Yin Xiao)
*Corresponding author

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Abstract: Because LNG has the advantages of high calorific value, low pollution and low price, this clean, high-quality fuel has attracted more and more attention from all walks of life. In recent years, LNG technology has developed rapidly, and the scale of installations has gradually increased, and a complete system project for LNG production and storage has been formed. The safe storage of LNG is vital to the development of the industry. The evaporation of LNG in the tank caused by the inflow of environmental heat is an important cause of overpressure and stratification and rollover in the tank, and affects the safe operation of the storage tank. Therefore, it is necessary to study the daily evaporation rate of the LNG storage tank and its influencing factors. Through the analysis of the cooling structure and heat exchange process of LNG storage tanks, a calculation method for heat leakage and daily evaporation rate of large LNG storage tanks is given, and the influence of solar radiation on the heat leakage of storage tanks is comprehensively considered. Taking a 30,000 cubic meter LNG storage tank as an example, the daily evaporation rate and influencing factors are calculated and analyzed. The results show that: (1) Daily evaporation rate of the LNG storage tank meets the relevant national design requirements. (2) The environmental temperature and full rate has a greater impact on the daily evaporation rate, and the environmental wind speed has a small impact on the daily evaporation rate. The calculation of the daily evaporation rate of the LNG storage tank and the analysis of influencing factors can provide a theoretical basis for the cold storage design and safe operation of the storage tank.

Keywords: LNG Storage Tank, Cold Insulation Structure, Heat Flow, Daily Evaporation Rate

1. Introduction

LNG storage peak shaving is an important peak shaving method to cope with the "gas shortage" caused by seasonal gas use such as clean heating. Large LNG storage tanks are important equipment for urban LNG peak shaving storage and distribution stations [1-3]. The interior of LNG storage tank is usually in a low temperature and slightly positive pressure state, and the inflow of environmental heat will cause LNG to evaporate, which may cause over pressure in the tank and LNG stratification and rollover accidents [4-5]. The cold preservation performance of LNG storage tanks is directly related to the safe operation of the storage tank, and the daily evaporation rate is an important indicator to measure the cold preservation effect of the storage tank [6]. WANG Wuchang et al establishes a mathematical model to predict the evaporation rate and pressure change in the tank [7]. It uses the model to analyze the influencing factors of the evaporation rate and proposes the "optimal diameter" and "optimal full rate" of the storage tank. Li Xiaoming et al gives a variety of LNG storage tank daily evaporation rate measurement and calculation methods, and discusses the application of various measurement methods in detail [8]. Jin Minghuang et al makes a simple calculation method of daily evaporation rate based on the characteristics of the cold insulation structure about LNG storage tanks, and demonstrates the feasibility of the calculation method through measured data [9]. The research on the daily evaporation rate of large-scale LNG storage tanks mainly focuses on the analysis of calculation methods, and there are few studies on the factors affecting the daily evaporation rate of storage tanks. Taking a 30,000 m^3 large-scale LNG storage tank as an example, this article gives a detailed calculation method for the daily evaporation rate and leakage heat of the

LNG storage tank. This paper also analyzes the influence of ambient temperature, ambient wind speed and full rate on the daily evaporation rate of the storage tank.

2. Basic Structure of Bimetallic LNG Storage Tank

The main structure of an LNG storage tank is usually composed of an outer tank, a stainless steel inner tank, a hot corner protection system, and a cold keeping system. The outer tank mainly has two forms: prestressed reinforced concrete outer tank and stainless steel outer tank. The main function of the outer tank is that when the inner tank ruptures and leaks, the outer tank can ensure that the storage tank can continue to store LNG safely for a period of time, and prevent LNG from leaking or releasing in large quantities and causing major safety accidents. At present, most of the large-scale LNG storage tanks under construction or in production in our country are the LNG storage tanks with a higher safety internal and external double tank structure [10]. Figure 1 and Figure 2 show the schematic diagram of the thermal insulation structure of a bimetallic LNG storage tank. The inner and outer tank bodies are all S30408 austenitic stainless steel structures. The insulation material is filled between the inner and outer tanks: the bottom insulation layer is mainly foam glass brick; the tank wall is a double-layer combination insulation material of expanded perlite and glass fiber mat, and the glass fiber mat can provide elastic support for the expanded perlite, It can also prevent the settlement of expanded perlite causing secondary material filling. There is a certain thickness of foam glass bricks at the bottom of the outer tank as a protective layer for hot corners; the stainless steel plate of the vault does not have cold insulation performance, and the cold insulation of the tank top mainly depends on the insulating glass wool layer at the suspended ceiling.

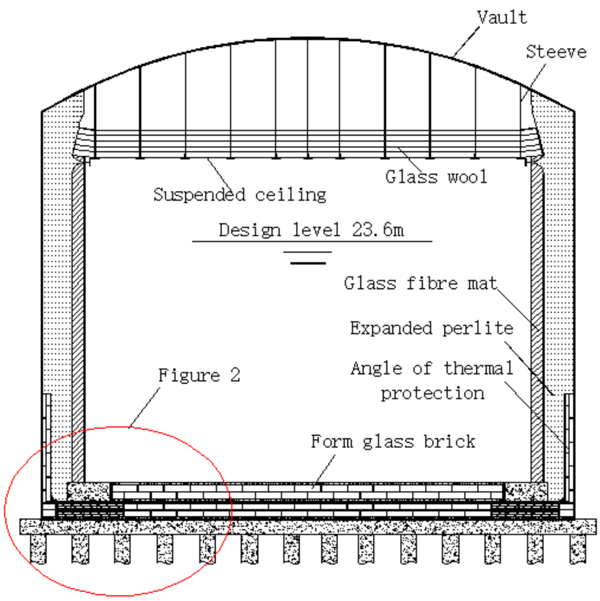

***Figure 1.** Schematic diagram of the cold insulation structure of a full-capacity LNG storage tank.*

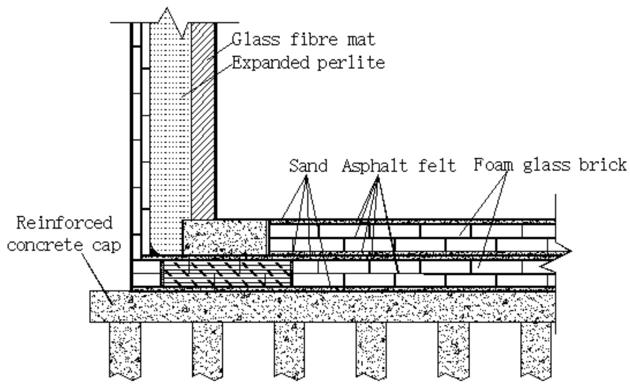

***Figure 2.** Schematic diagram of partial cold insulation structure of full-capacity LNG storage tank.*

3. Annual Gas Temperature

The heat leakage of large-scale LNG storage tanks mainly includes three aspects: tank top heat leakage, tank wall heat leakage and tank bottom heat leakage. The heat leakage of tank top and tank wall is greatly affected by solar radiation, their heat leakage changes greatly under solar radiation. Based on the structural characteristics of the LNG storage tank, the theoretical model for calculating the leakage heat of the storage tank is analyzed and established. In order to simplify the calculation, the following assumptions are made on the model:(1) The materials of each layer of the storage tank are tightly combined, ignoring the contact thermal resistance between adjacent layers.(2) The tank is in a gas-liquid equilibrium state, and the temperature distribution in tank is uniform and equal.(3) The storage tank and the external environment are in a steady state heat transfer process, and the temperature of each part of the storage tank does not change with time.(4) The heat absorbed by the storage tank from the outside is all used to evaporate to produce BOG, and the BOG produced by evaporation can be recovered and processed in time by the BOG recovery system, and the pressure in the tank remains unchanged.

3.1. Analysis of Tank Wall Heat Leakage

The main form of heat leakage of the tank wall is the heat transferred to the storage tank by air in the form of convective heat transfer. On the one hand, because the storage tank is in a closed state, the pressure change in the LNG storage tank causes the thermal characteristics of the saturated LNG in the tank to change [11], which affects the heat exchange between the inside of the storage tank and the outside world. On the other hand, due to the large difference in the convective heat transfer performance between LNG liquid and BOG, the convective heat transfer intensity of the gas phase space of the LNG storage tank and the low-temperature LNG on the inner wall of the storage tank are different, which affects the heat flux of the storage tank wall, we need to separately consider the heat flow of the corresponding wall of BOG gas space and LNG liquid space in the tank. The heat flow calculation of the side wall of the storage tank can be calculated according to equations (1) and (2).

$$\Phi_{1\text{-}1}=\frac{\left(T_{\mathrm{f}}-T_{\mathrm{g}}\right)\pi L_1}{\frac{1}{h_{\mathrm{f}}d_{\mathrm{f}}}+\sum\frac{1}{2\lambda_i}\ln\frac{d_{i+1}}{d_i}+\frac{1}{h_{\mathrm{L}}d_{\mathrm{L}}}} \quad (1)$$

$$\Phi_{1\text{-}2}=\frac{\left(T_{\mathrm{f}}-T_{\mathrm{g}}\right)\pi L_2}{\frac{1}{h_{\mathrm{f}}d_{\mathrm{f}}}+\sum\frac{1}{2\lambda_i}\ln\frac{d_{i+1}}{d_i}+\frac{1}{h_{\mathrm{g}}d_{\mathrm{L}}}} \quad (2)$$

Where $\Phi_{1\text{-}1}$ is LNG liquid phase space of storage tank, W, $\Phi_{1\text{-}2}$ is heat flow in BOG gas phase space, W, T_{f} is ambient temperature, K, T_{g} is temperature in LNG storage tank, K, L_1 is LNG height, m, L_2 is BOG height, m, d_{i+1} is the outer diameters of each layer of insulation material, m, d_i is the inner diameters of each layer of insulation material, m, d_{f} is outer tank outer diameter, m, d_{L} is inner tank inner diameter, m, h_{g} is the convective heat transfer coefficient of BOG to the inner wall of the storage tank, W/(m^2·K), h_{f} is convective heat transfer coefficient of air to the outer wall of the storage tank, W/(m^2·K), h_{L} is convective heat transfer coefficient of LNG to the inner tank wall, W/(m^2·K).

Regarding the convective heat transfer on the outer wall of the storage tank, when the air velocity around the storage tank is zero, it appears as natural convection heat transfer in a large space, and the convective heat transfer coefficient on the wall of the storage tank is small. When the air starts to flow, it changes to external forced convection heat transfer. The convective heat transfer coefficient of the tank wall increases greatly with the increase of air velocity. The change of the convective heat transfer coefficient of the outer wall of the storage tank with the wind speed can be calculated by the following formula [12]:

$$h_{\mathrm{f}}=6.02+3.46v \quad (3)$$

Where v is ambient wind, speed, m/s.

3.2. Analysis of Tank Bottom Heat Leakage

The heat leakage Φ_2 at the bottom of the LNG storage tank mainly consists of two parts. One is the heat transferred $\Phi_{2\text{-}1}$ to the outer wall of the storage tank by the air in the form of convective heat exchange, and then the heat transferred to the storage tank through the storage tank insulation layer. The other is the heat transferred $\Phi_{2\text{-}2}$ from the soil to the storage tank in the form of heat conduction through the load-bearing column and the insulation layer. Since the temperature difference between the load-bearing column and the surrounding environment is small, the convective heat transfer is ignored. The calculation formula of the heat flow at the bottom of the storage tank can be obtained from the analysis.

$$\Phi_{2\text{-}1}=\frac{T_{\mathrm{f}}-T_{\mathrm{g}}}{\frac{1}{S_1h_{\mathrm{f}}}+\sum\frac{\delta_i}{S_1\lambda_i}+\frac{1}{S_1h_{\mathrm{L}}}} \quad (4)$$

$$\Phi_{2-2}=\frac{T_{\mathrm{f}}-T_{\mathrm{g}}}{\sum\frac{\delta_i}{S_2\lambda_i}+\frac{1}{S_2h_{\mathrm{L}}}} \quad (5)$$

Where S_1 is the area of the tank bottom in direct contact with the air, m^2, S_2 is the total area of the load-bearing column, m^2, λ_i is thermal conductivity of each layer of the tank bottom, W/(m·K), δ_j is thickness of each layer of the tank bottom, m.

3.3. Analysis of Tank Top Heat Leakage

For the bimetallic LNG storage tanks, the insulation of the tank roof mainly relies on the insulation layer at the ceiling, and the dome material does not have insulation performance. It can be approximated that the internal and external surface temperature of the dome is the same, and the value is approximately equal to the ambient temperature. The radiant heat transfer from the dome to the ceiling and the heat transfer from the dome to the ceiling through the tank roof gas are the main forms of tank roof heat leakage. The heat transfer from the dome to the tank top fluid is equal to the heat transfer from the tank top fluid to the convective heat transfer of the ceiling:

$$S_3h_1\left(T_{\mathrm{v}}-T_1\right)=S_4h_1\left(T_1-T_{\mathrm{c}}\right) \quad (6)$$

Where S_3 is Vault area, m^2, S_4 is ceiling area, m^2, T_{v} is vault temperature, h_1 is the surface-to-wall heat transfer coefficient of BOG on the top of the tank, W/(m^2·K), T_1 is the temperature tank of the BOG on the top of the tank, K, T_{c} is surface temperature of suspended ceiling, K.

The heat transferred from the top of the tank to the ceiling is equal to the heat transferred from the ceiling to the inside of the tank:

$$\Phi_3=\frac{\sigma\left(T_{\mathrm{v}}^4-T_{\mathrm{c}}^4\right)}{\frac{1-\varepsilon_1}{S_3\varepsilon_1}+\frac{1}{S_4X_{3,4}}+\frac{1-\varepsilon_2}{S_4\varepsilon_2}}+S_3h_1\left(T_{\mathrm{f}}-T_1\right)=\frac{\left(T_{\mathrm{c}}-T_{\mathrm{g}}\right)S_4}{\sum\frac{\delta_i}{\lambda_i}+\frac{1}{h_{\mathrm{g}}}} \quad (7)$$

Where Φ_3 is heat flux at the top of the tank, W, σ is Stefan-Boltzmann constant, W/(m^2·K^4), ε_1 is emissivity of the inner surface of the vault, ε_2 is emissivity of the upper surface of the suspended ceiling, $X_{3,4}$ is angle factor.

Combining the two equations (6) and (7) can obtain the top fluid temperature and the ceiling surface temperature, and then enter equation (7) to obtain the tank top heat flow (Φ_3).

3.4. The Influence of Solar Radiation on the Heat Leakage of Storage Tanks

When solar radiation exists, the storage tank absorbs solar radiant heat to increase the temperature of the outer surface, which causes the heat leakage of the storage tank to increase. Assuming that the annual average single-day radiation time is 12 hours, the wall temperature under solar radiation can be calculated as follows [13].

The half-day solar radiation received per unit area on the roof of the storage tank is:

$$q_1 = h_{oriz} \cdot \gamma \tag{8}$$

Where h_{oriz} is half-day horizontal solar radiation gain at the latitude (The heat obtained by the surface in a horizontal direction per unit area within 12h due to solar radiation), W/m^2, γ is solar radiant heat gain factor.

The half-day solar radiation per unit area on the side wall of the storage tank is:

$$q_2 = v_{ert} \cdot \gamma \tag{9}$$

Where v_{ert} is the solar radiation gain in the vertical direction of the half-day at the latitude, W/m^2.

According to the law of conservation of energy, part of the heat radiated by the sun to the storage tank is absorbed, part of the heat is transferred to the surface, and the rest is re-radiated after reflection. Surface heat flux=Absorb heat + Surface heat transfer-Radiant heat. The following relations can be obtained:

$$h_f\left(T - T_s\right) = \frac{\alpha q}{12} + h_f\left(T_f - T_s\right) - \varepsilon \Delta R \tag{10}$$

Where α is absorption factor on the outer surface of the tank, q is half-day solar radiation per unit area on the roof or side wall of the storage tank, W/m^2, h_f is convection heat transfer coefficient of the outer surface of the storage tank, W/(m^2·K), T is the outer surface temperature of the storage tank after receiving solar radiation, K, T_s is outer surface temperature of storage tank, K, T_s is air temperature, K, ε is normal radiance, ΔR is the difference between the long-wave radiation and the light wave energy emitted by the black body.

From this, the calculation formula for the temperature of the outer surface of the storage tank after heating can be obtained:

$$T = \frac{\alpha q}{12h} + T_f - \frac{\varepsilon \Delta R}{h} \tag{11}$$

According to formula (11), the dome temperature and tank side wall temperature under solar radiation can be calculated. According to formulas (1), (2) and (7), the heat leakage of the tank wall under solar radiation ($\Phi_{R1\text{-}1}$ and $\Phi_{R1\text{-}2}$) can be deduced and the calculation formula of tank roof leakage heat (Φ_{R3}), in which the upper surface temperature of the suspended ceiling under solar radiation is the same as the calculation method under no radiation.

3.5. Calculation of Static Daily Evaporation Rate of Storage Tank

Taking into account the effect of solar radiation on an average of 12 hours in a single day, the total heat flow of the storage tank is that:

$$\Phi_{all} = \Phi_2 + \frac{\Phi_{1-1} + \Phi_{1-2} + \Phi_3}{2} + \frac{\Phi_{R1-1} + \Phi_{R1-2} + \Phi_{R3}}{2} \tag{12}$$

Where Φ_{all} is the total heat flow of the storage tank.

The static daily evaporation rate (BOR) of an LNG storage tank refers to the percentage of LNG boil-off gas (BOG) produced by evaporation within 24 hours of the total mass of LNG in the storage tank after the storage tank reaches thermal equilibrium in a static state. According to the definition of static daily evaporation rate, the calculation formula is that:

$$\eta = \frac{86400\Phi_{all}}{\rho \cdot V \cdot \gamma_L} \tag{13}$$

Where η is static daily evaporation rate, γ_L is latent heat of vaporization of LNG, J/kg, ρ is density of LNG, kg/ m^3, V is LNG volume in the storage tank, m^3.

4. Example Calculation

The above calculation method is used to calculate and analyze the daily evaporation rate of a 3×10^4 m3 bimetallic LNG storage tank in Jinan at standard atmospheric pressure and rated filling height. The cold insulation structure of the LNG storage tank is shown in Figure 1 and Figure 2, and its structural parameters and main cold insulation material parameters are shown in Table 1 and Table 2.

The value of each parameter is put into the formula to get the leakage heat of the LNG storage tank in the natural static state, as shown in Table 3. The 24 hours heat leakage of the LNG storage tank is 4.3 GJ. According to the physical parameters of LNG when the pressure is standard atmospheric pressure (the density is 496.5 kg/m^3, the latent heat of vaporization is 510.42kJ/kg), the evaporation mass of LNG under natural heat leakage per day of the case storage tank is 8431.6kg. The static daily evaporation rate at the rated liquid filling height is 0.0532%, which meets the design specifications for large-scale LNG storage tanks, and the daily evaporation rate of LNG storage tanks with a tank capacity of 10,000 to 50,000 m^3 ≤0.08% [14].

Table 1. *Basic parameters of a full-capacity LNG storage tank.*

Parameters of the storage tank	The value of the parameter
Inner diameter of outer tank/m	21.75
Inner diameter of inner tank/m	20.75
The height of the inner tank/m	25.5
Annual average ambient temperature/°C	15.15
LNG storage temperature/°C	-162
Rated full height/m	23.6

Table 2. *Physical parameters of cold insulation materials for a full-capacity LNG storage tank.*

The structure of the tank	Material	Thickness × Number of layers×10^{-3}/m	Thermal Conductivity /(W/m^2)
Inner tank/Outer tank/Tank top	O6Cr18Ni9Cu2	20	16.3
	Expanded perlite	680	0.045
Insulation layer of tank wall	Glass fiber mat	300	0.058
	Angle of thermal protection	250	0.058
Susoended ceiling	Glass wool	1000	0.058
	Sand	50×4	0.269
Tank bottom insulation	Foam glass brick	160×4	0.058
	Asphalt felt	6×5	0.17
Concrete cap	Concrete	1000	0.70
Load-bearing column with a diameter of 1 meter (144 pieces)	Concrete	1500	0.70

Table 3. *Calculation results of heat leakage of LNG storage tanks.*

	No solar radiation/W	solar radiation/W
Heat flow at the bottom of the tank	17819.6	17819.6
Heat flux of the tank wall	17656.1	18139.8
Heat flux at the top of the tank	13703.9	14449.1

5. Analysis of Influencing Factors of Static Daily Evaporation Rate of Storage Tanks

5.1. Influence of Ambient Temperature

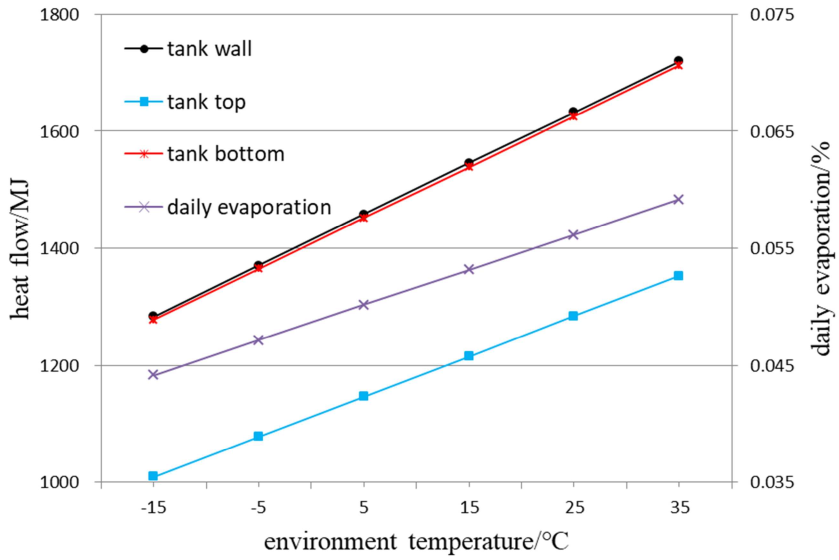

Figure 3. *Variation curves of leakage heat and daily evaporation rate of LNG storage tank with ambient wind speed.*

The ambient wind speed around the storage tank mainly influences the leakage heat and evaporation rate of the storage tank by changing the convective heat transfer coefficient of the external surface of the storage tank [15]. The convective heat transfer coefficient of the external surface of the storage tank under different ambient wind speeds is calculated according to Formula (3). The variation of heat leakage and evaporation rate with ambient air speed under rated full height and average ambient temperature of 15.15°C in the tank is shown in Figure 4: with the increase of ambient air speed, the heat leakage and evaporation rate of the tank gradually increase, but the growth rate gradually decreases. When the ambient air speed reaches 15m/s, the growth rate is close to zero, and the evaporation rate of the tank reaches the maximum value of 0.0533%. When the ambient wind speed changes from 0 to 21m/s, the evaporation rate of the storage tank increases by 0.0003%, and the ambient wind speed has an influence on the evaporation rate of the storage tank, but the influence is small. Environmental wind speed has a great influence on the convective heat transfer coefficient of the outer surface of the storage tank, but it has little influence on the daily evaporation rate of the storage tank, which is mainly due to the thick insulation layer of the storage tank and the dominant thermal conductivity at the insulation layer of the storage tank. Although the change of environmental wind speed changes the convective heat transfer resistance of the storage tank surface to a great extent, its variable is very small compared with the overall thermal resistance of the storage tank wall, so the change of environmental wind speed has little influence on the daily evaporation rate of the storage tank.

5.2. Influence of Ambient Wind Speed

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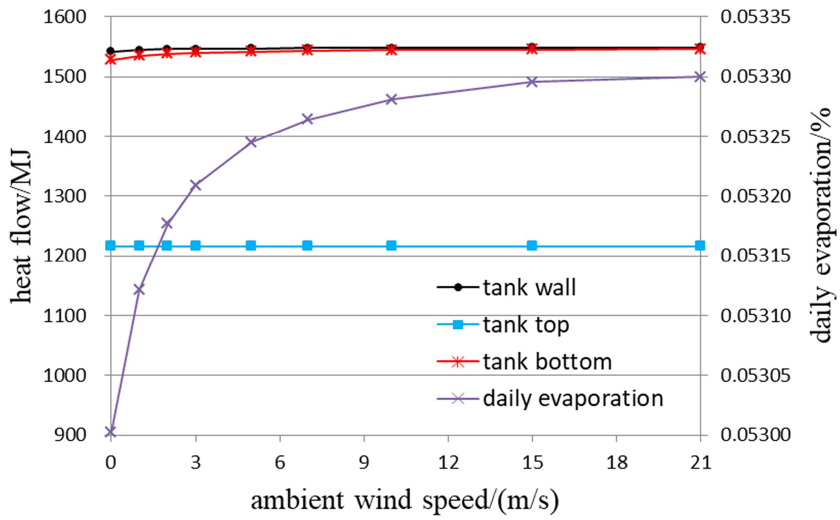

Figure 4. *Variation curves of leakage heat and daily evaporation rate of LNG storage tank with ambient wind speed.*

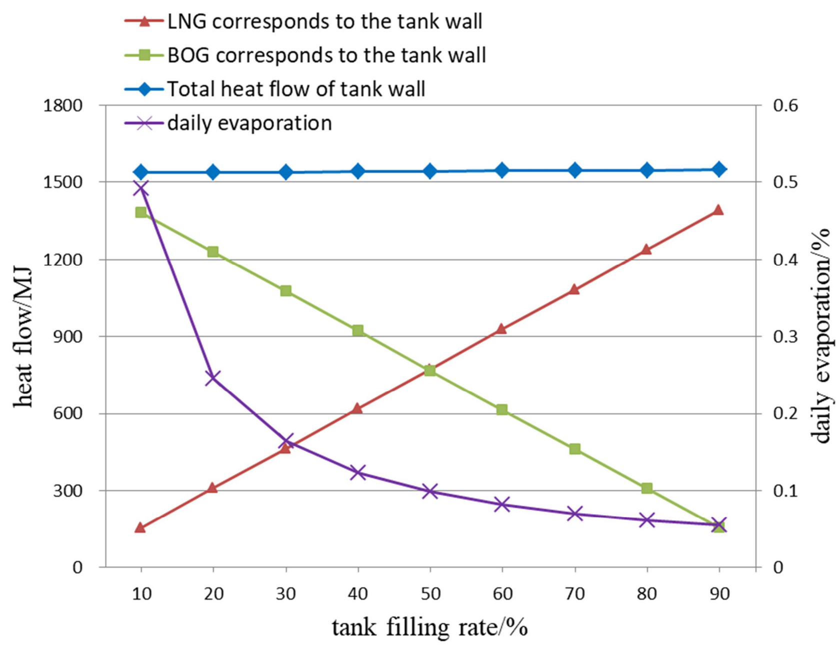

Figure 5. *Variation curves of leakage heat and daily evaporation rate of LNG tank wall with full rate.*

5.3. The Influence of Tank Filling Rate

Figure 5 shows the curves of sidewall heat leakage and daily evaporation rate with the full rate of LNG storage tank when the average ambient wind speed is 2.6m/s and the average ambient temperature is 15.15°C: With the increase of tank filling rate, the leakage heat of tank side wall changes linearly. For every 10% increase of tank filling rate, the heat absorbed by LNG evaporation gas in gas phase space decreases by 153.49MJ, while the heat absorbed by LNG in liquid phase space increases by 154.73 MJ, and the total leakage heat of tank side wall increases by 1.24 MJ. The leakage heat of tank side wall changes little with tank filling rate. However, the daily evaporation rate of the storage tank varies greatly with the full rate of the storage tank. The main reasons are as follows: Because of the better thermal insulation performance of the tank wall insulation layer, with the increase of the tank's full rate, the heat leakage from the side wall changes little, but the total LNG in the tank increases greatly, which leads to a great reduction in the proportion of LNG evaporated in a single day to the total LNG in the tank. When the tank's full rate changes from 10% to 90%, the evaporation rate changes from 0.491% to 0.0547%, and the evaporation rate is reduced by about 9 times. Therefore, increasing the full rate of storage tanks can improve the utilization efficiency of BOG treatment system and increase the economic benefits of long-term storage of LNG in storage tanks.

6. Conclusion

(1) According to the structural characteristics of LNG storage tanks, the calculation methods of the heat flux at the tank top, tank wall and tank top with and without solar radiation are given through analysis, and the calculation methods of the total heat flux and daily evaporation rate of the storage tanks under the average radiation of 12h per day are also given. The daily evaporation rate of a 30,000 m^3 bimetallic LNG storage tank is calculated to be 0.0532% under the conditions that the annual average ambient temperature is 15.15°C, the pressure in the tank is standard atmospheric pressure, the average wind speed is 2.6m/s, and the rated full rate. The results show that the daily evaporation rate meets the design specification requirements, but there is still about 104 m^3 evaporation per day, so effective collection measures should be taken.

(2) The effects of ambient temperature, ambient wind speed and tank filling rate on the daily evaporation rate are analyzed. The results show that ambient temperature and filling rate have great influence on the daily evaporation rate of the tank and are the main factors affecting the daily evaporation rate of the tank. The ambient wind speed has little effect on the daily evaporation rate of storage tank.

(3) In fact, the heat leakage of LNG storage tank is a complex multi-dimensional unsteady heat transfer problem, which is regarded as a simple one-dimensional steady heat transfer problem in calculation in this paper. There is a certain deviation between the calculated results and the actual situation. In order to improve the calculation accuracy, the heat transfer process can be analyzed in depth later. In addition, the current numerical simulation analysis software has been widely used in the analysis of heat transfer process, and the author will use relevant software to carry out numerical simulation analysis of the research in the later period.

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