

Study on the Engineering Application of LNG Accident Consequence Model in the Design of Terminal Sump

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Abstract. In order to provide a theoretical basis for the design of the LNG terminal sump, this paper proposes a suitable mathematical model and solution method by analyzing the physical process of evaporation diffusion and thermal radiation of the sump. Combined with the engineering practice, a lot of calculations have been carried out on the vapor diffusion concentration and pool fire thermal radiation intensity of the terminal sump, and the correlations between the vapor concentration and thermal radiation intensity and their influencing factors have been quantitatively calculated. Based on the analysis of the calculation results, it is concluded that the vapor concentration and thermal radiation value at the fire control room of the wharf are strongly related to the equivalent diameter of the sump and the distance from the fire control room to the sump. Among them, the distance from the fire control room to the sump is more closely related to the vapor concentration, and the equivalent diameter of the sump is more closely related to the thermal radiation; Keeping 19.2~33.8meters between the fire control room and the sump can basically ensure that the vapor concentration at the fire control room does not exceed the standard; In order to ensure that the thermal radiation at the fire control room does not exceed the standard, the distance between the fire control room and the sump should not be less than 15meters, and the equivalent diameter of the sump should not be greater than 7meters. The research methods and conclusions proposed in this paper can provide useful reference for engineering designers, and also build a bridge for mutual reference and application for theoretical research and engineering practice.

Keywords: LNG terminal, sump size, evaporation diffusion, pool fire thermal radiation, accident consequence model.

1. Introduction

The sump is a collecting place when LNG leaks from the pipeline on the terminal. If the collected LNG encounters an ignition source, it may cause a pool fire, or absorbs heat from the surrounding environment and it may evaporate and diffuse. The fire control room is a regional major place with relatively concentrated personnel on the dock, which has restrictive requirements on the evaporation and diffusion range of the sump and the pool fire heat radiation intensity. The opening area and setting position (distance from the fire control room) of the sump have a direct impact on the steam concentration and thermal radiation at the fire control room, which is also the key and difficult point in the design of the LNG terminal.

According to the survey, the sump designs of LNG terminals are different, which are built and under construction in China, as shown in Table 1 below [1-4]. The setting positions of the sumps are also different, such as at the back edge of the mooring pier, the back edge of the working platform, the back edge of the berthing pier [5]. These positions differ greatly from the fire control room. In the industry, there is no consensus on the opening area and setting position of the sump. The design schemes are diverse, the calculation methods are varied, and the design lacks theoretical. Therefore, it is necessary to deeply study the basic laws of evaporation diffusion and pool fire thermal radiation of LNG terminal sump, so as to provide a theoretical reference for the sump design.

Table 1. Statistical table of the sizes of LNG terminal sumps built and under construction in China

LNG terminal	Sump size (length × wide × High)	Sump volume
Fujian LNG terminal I phase	5m×5m×3.7m	92.5m ³
Zhejiang LNG terminal	5m×5m×4.15m	103.75m ³
Tianjin LNG terminal of National Pipeline Network Group	6m×6m×3m	108m ³
A LNG terminal under construction in Zhoushan, Zhejiang	8m×5m×3m	120m ³
Hainan LNG terminal of National Pipeline Network Group	5m×4m×5m	120m ³
A LNG terminal under construction in Rudong, Jiangsu	6m×6m×3.5m	126m ³
Dalian LNG terminal of National Pipeline Network Group	5m×5m×6m	150m ³

In order to quantitatively study the relationship between steam diffusion and pool fire thermal radiation and the open area of the sump, and the distance between the sump and the fire control room, a calculation model suitable for engineering practice is established, based on the physical process analysis of evaporation diffusion and thermal radiation of the sump. And a research conclusion with engineering application value is given through quantitative calculation.

2. Physical Process of Evaporation Diffusion and Thermal Radiation in LNG Terminal Sump

During loading and unloading, LNG leakage may occur at the wharf due to pipeline corrosion, poor flange sealing and other reasons. After the leaked LNG is collected through the liquid collecting tray below the leakage point, it is transferred to the sump by using the liquid guide ditch or diversion pipe.

When LNG appears in the terminal sump, three low-temperature detectors will send the detection signal to the fire control room and trigger the audible and visual alarm. At the same time, the high expansion foam fire extinguishing system above the sump is interlocked and started. After the foam covers the liquid level of LNG, its evaporation rate is controlled, and external open flames and sparks are isolated. Evaporated natural gas diffuses in the air, especially in the downwind direction. When it diffuses to the fire control room, it may cause suffocation of indoor personnel or explosion when encountering indoor non-explosion-proof equipment [6]. Therefore, 10.3.5 of Code for Fire Protection Design of Petroleum and Natural Gas Engineering (GB50183-2014) requires that the evaporation diffusion isolation area (the boundary of the isolation zone is 50% of the lower explosive limit of natural gas) should not cover the fire control room [7].

In addition, when the LNG collected in the sump encounters lightning, static electricity and other sparks, it can cause pool fire. If the only flame detector in the sump fails and the high expansion foam extinguishing system is not interlocked in time, it is difficult to extinguish the pool fire immediately. The thermal radiation generated by pool fire combustion will have adverse effects on the fire control room. Therefore, 10.3.4 of Code for Fire Protection Design of Petroleum and Natural Gas Engineering (GB50183-2014) requires that the thermal radiation of fire control room during pool fire shall not exceed 9000W/m².

3. Mathematical model of evaporation and diffusion in LNG terminal sump

The vapor concentration at the fire control room is related to the distance between the fire control room and the sump, the opening area of the sump, the wind speed [8] and other factors. At present, LNG evaporation and diffusion are mainly studied by experiment and numerical calculation. Famous experimental researches include Shell experiment, Burro experiment, Esso experiment, Falcon experiment, Coyote experiment, wind tunnel experiment of Colorado State University, etc. [9]. The mature numerical calculation models include Gaussian plume model, Gaussian puff model, box model, shallow model, BM model, etc. [10,11]. Although experimental research has the advantages of intuitive results and reliable data, it also has the disadvantages of single experimental scenario, poor model generalization, long experimental cycle, and large investment. Therefore, numerical calculation method is selected in this paper.

Among the existing classical numerical calculation models, the box model, shallow model and BM model are heavy gas diffusion models, which are not applicable to the diffusion of natural gas with density lower than air. Gauss plume model is often used for continuous point source diffusion calculation, and is not applicable to the total volatilization scenario of LNG terminal sump. Therefore, the Gaussian puff model is selected for this study:

$$C(x, y, z, t) = \frac{\bar{m}d^2}{8\sqrt{2}\pi^{1/2}\sigma_x\sigma_y\sigma_z} \exp\left\{-\frac{1}{2}\left[\frac{(x-vt)^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right]\right\} \times \left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\} \quad (1)$$

Where, C is the gas concentration at the time (x, y, z) when the vapor diffuses to t , kg/m^3 ; \bar{m} is the average rate of LNG gasification to vapor per unit liquid level, kg/m^2 ; D is the equivalent diameter of the sump, m ; x, y, z are space coordinates, m ; T is the diffusion time of LNG, s ; V is the ambient wind speed, m/s ; H is the effective height of the leakage source, m ; $\sigma_x, \sigma_y, \sigma_z$ is the diffusion parameter in x, y and z directions respectively, m .

The effective height H of the leakage source is the height above the ground of the gas cloud center when the gas cloud formed by the leakage gas is basically horizontal. For LNG terminal, if the geometric height of the liquid level in the sump above the ground is 0, the semi empirical formula [12] can be used for the effective height H of the leakage source:

$$H = 2.4u_s d/v \quad (2)$$

Where, u_s is the gas cloud outlet velocity, m/s .

Considering that the location of LNG wharf sump is wide and flat, diffusion parameters $\sigma_x, \sigma_y, \sigma_z$. The relationship between z and downwind distance x is as follows:

$$\sigma_x = \sigma_y = 0.06x^{0.92} \quad (3)$$

$$\sigma_z = 0.15x^{0.70} \quad (4)$$

The volatilization of the sump belongs to the volatilization of the stable source field, and the center of the coordinate system can be taken as the center of the sump $x=vt$. The sump is the ground leakage source $z=0$. When $y=0$, the concentration distribution on the x -axis in the diffusion of the sump can be obtained:

$$C(x) = \frac{\bar{m}d^2}{4\sqrt{2}\pi^{1/2}\sigma_x\sigma_y\sigma_z} \exp\left\{-\frac{H^2}{2\sigma_z^2}\right\} \quad (5)$$

Further, formulas 2~4 are substituted into formula 5 to obtain the vapor concentration in the x direction:

$$C(x) = \frac{184.74\bar{m}d^2}{x^{2.54}} \exp\left\{-\frac{128u_s^2 d^2}{v^2 x^{1.4}}\right\} \quad (6)$$

4. Mathematical model of pool fire thermal radiation in LNG terminal sump

There are many methods to calculate the thermal radiation of pool fire, and the semi-empirical model has been widely used in engineering due to its simple application and reasonable and reliable results [13]. At present, more mature semi-empirical models include point source model, Shokri-Beyle model and Mudan model. The Mudan model regards the pool flame as a vertical or inclined cylindrical radiation source, which can be used to calculate the thermal radiation flux received by the receptor from the pool flame under the conditions of no wind or wind [14,15]. Therefore, the model is applicable to the fire scenario of LNG terminal sump, and the thermal radiation $q(r)$ of the receptor at r is:

$$q(r) = q_0(1 - 0.0058 \ln r)V \quad (7)$$

Where, $q(r)$ is the heat flux received by the receptor, kW/m²; R is the horizontal distance from the receiver (fire control room) to the sump, m; q_0 is the heat flux on the flame surface, kW/m²; V is the view factor.

It is assumed that the energy radiates uniformly from the side and top of the cylindrical flame to the surrounding, and the flame surface heat flux q_0 can be calculated by the following formula:

$$q_0 = \frac{0.25\pi d^2 \Delta H_c m_f f_h}{0.25\pi d^2 + \pi dL} \quad (8)$$

Where, d is the equivalent diameter of the sump, m; L is the flame height, m; ΔH_c is combustion heat, kW/m²; m_f is the combustion rate, kg/m²·s; f_h is the thermal radiation coefficient, taking 0.15.

The view factor V is related to the ratio of the distance from the receptor to the vertical axis of the flame to the flame radius s and the ratio of the flame height to the diameter h .

$$V = \sqrt{(V_V^2 + V_H^2)} \quad (9)$$

$$V_H = \frac{1}{\pi}(A - B) \quad (10)$$

$$V_V = \frac{1}{\pi} \tan^{-1} (h/(s^2 - 1)^{0.5})/s + h(J - K)/s \quad (11)$$

$$A = (b - 1/s) \left\{ \tan^{-1} \left[\frac{(b+1)(s-1)}{(b-1)(s+1)} \right]^{0.5} \right\} / (b^2 - 1)^{0.5} \quad (12)$$

$$B = (a - 1/s) \left\{ \tan^{-1} \left[\frac{(a+1)(s-1)}{(a-1)(s+1)} \right]^{0.5} \right\} / (a^2 - 1)^{0.5} \quad (13)$$

$$J = \left[\frac{a}{(a^2 - 1)^{0.5}} \right] \tan^{-1} \left[\frac{(a+1)(s-1)}{(a-1)(s+1)} \right]^{0.5} \quad (14)$$

$$K = \tan^{-1}((s - 1)/(s + 1))^{0.5} \quad (15)$$

$$a = (h^2 + s^2 + 1)/(2s) \quad (16)$$

$$b = (1 + s^2)/(2s) \quad (17)$$

In the formula, s is the ratio of the distance from the receiver to the sump to the flame radius (equivalent radius of the sump). h is the ratio of flame height to diameter (equivalent diameter of liquid sump). A, B, J, K, V_H, V_V are intermediate variables introduced for convenience of description.

The relationship between the flame height L and the equivalent diameter d of the sump is as follows:

$$L = 42d \times [m_f / (\rho_0 \sqrt{gd})]^{0.61} \quad (18)$$

Where, ρ_0 is the air density, kg/m³.

Substitute Formulas 8~18 into Formula 7 to obtain the heat flux received by the surrounding receptors when the pool fire occurs in the LNG terminal sump.

5. Calculation results and quantitative analysis of evaporation and diffusion in the sump

According to the evaporation and diffusion model of the sump above, this section quantitatively studies the following contents:

(1) Quantitative relationship between steam concentration and equivalent diameter of the sump, wind speed, and distance between fire control room and the sump. The main and secondary factors of steam concentration are given through correlation analysis.

(2) The quantitative relationship between the radius of the diffusion isolation zone (where the concentration of natural gas is 50% of the lower explosive limit) and the equivalent diameter of the sump and the wind speed.

The LNG density is calculated as 480kg/m^3 , the liquid volume in the sump is calculated as 48000kg , and the rising rate of the gas cloud on the LNG volatilization in the sump is calculated as 1m/s . Using the model given above, the steam concentration at the fire control room can be obtained as shown in Figure 1 to Figure 3 below:

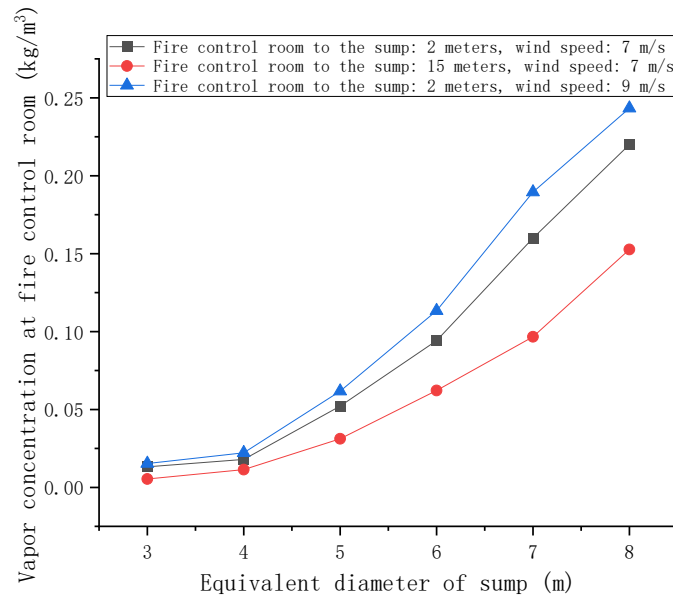


Fig. 1 Effect of the Equivalent Diameter of the Sump on Evaporation Diffusion

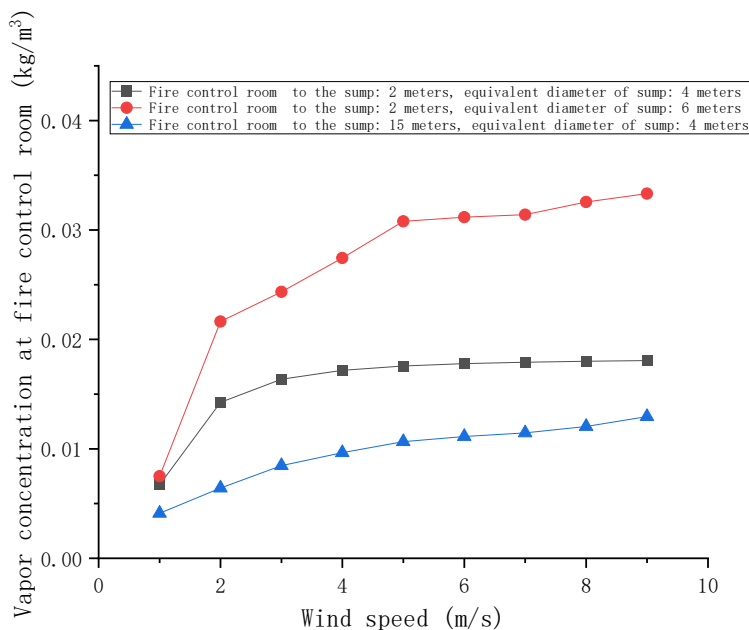


Fig. 2 Influence of wind speed on evaporation diffusion

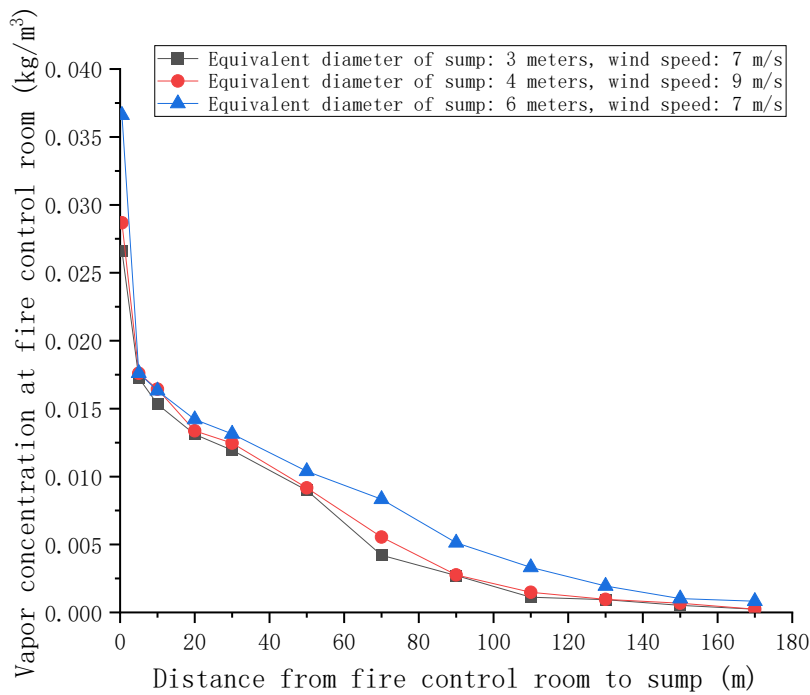


Fig. 3 Relationship between steam concentration and distance in fire control room

It can be seen from Figure 1 and Figure 2 that the steam concentration at the fire control room increases with the increase of the equivalent diameter of the sump and the wind speed. It can be seen from Figure 3 that the farther the distance from the fire control room to the sump is, the lower the steam concentration at the fire control room is. It is further calculated that the correlation coefficients between the steam concentration and the equivalent diameter of the sump, the wind speed, and the distance from the fire control room to the sump are 0.884, 0.749, and -0.923, respectively. It can be seen that the vapor concentration changes significantly with the change of the equivalent diameter of the sump and the distance from the fire control room to the sump; The effect of wind speed on steam concentration is relatively insignificant.

Under the condition that the vapor concentration at the boundary of the diffusion isolation zone is known to be 5% of the lower explosion limit (the vapor concentration limit at the fire control room), the quantitative relationship between the radius of the diffusion isolation zone and the wind speed and the equivalent diameter of the liquid collecting pool is calculated. We need to solve the implicit equation about variable x in equation 6 above. In this paper, Visio Basic software is used for programming, and the enumeration method is used to solve x iteratively, as shown in Table 2, Figure 4, and Figure 5.

Table 2. Calculation results of radius of diffusion isolation zone

Equivalent diameter of sump /m	Radius of diffusion isolation zone /m					
	wind speed	wind speed	wind speed	wind speed	wind speed	wind speed
	1m/s	2m/s	3m/s	5m/s	7m/s	9m/s
3	26.1	8.3	4.3	1.9	1.1	0.5
4	42.6	13.2	6.8	3.1	1.8	1.2
5	62.7	19.2	9.8	4.3	2.6	1.7
6	86.6	26.1	13.3	5.8	3.4	2.3
7	114.5	33.8	17.2	7.4	4.3	2.9
8	155.3	42.6	21.4	9.2	5.4	3.6

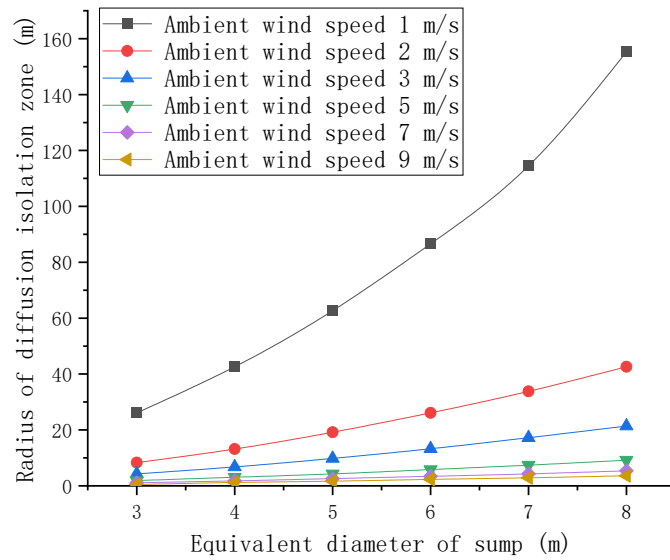


Fig. 4 Effect of the Equivalent Diameter of the Sump on Radius of the Diffusion Isolation Zone

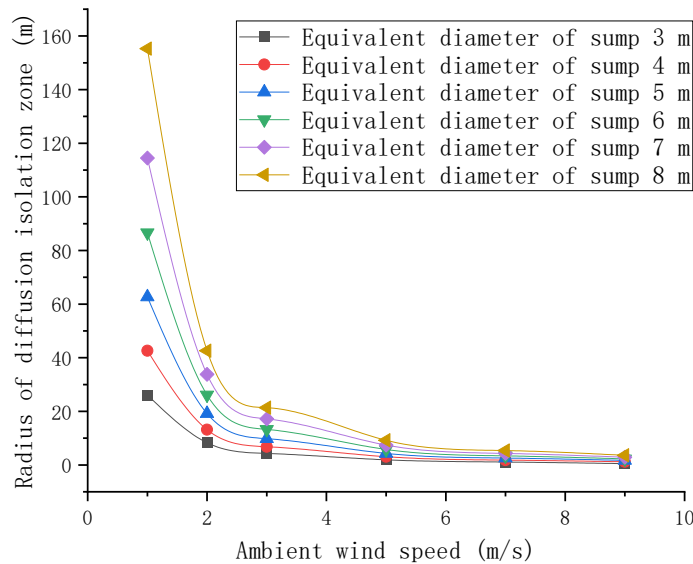


Fig. 5 Influence of wind speed on radius of diffusion isolation zone The conclusions of the comprehensive analysis are as follows:

(1) Compared with Figure 2 and Figure 5, when the distance between the fire control room and the sump is fixed, the greater the wind speed is, the more steam diffuses to the fire control room, and the greater the steam concentration is; However, strong wind also has the effect of diluting the concentration of steam. When the distance between the fire control room and the sump reaches a certain value, the dilution effect of wind speed will be enhanced. When arranging the sump and fire control room of the wharf, not only the evaporation and diffusion capacity of the strong wind can be increased, but also the dilution effect of the strong wind on the steam should be considered.

(2) The effect of the distance from the fire control room to the sump on the concentration of steam at the fire control room is stronger than that of the equivalent diameter of the sump. In the design of the wharf, the steam concentration at the fire control room can be controlled by adjusting the distance from the fire control room to the sump.

(3) It can also be seen from Table 2 that when the ambient wind speed is 2 m/s, the radius of the vapor diffusion isolation zone under the opening area of the common sump (equivalent diameter is 4 m~7 m) is about 19.2 m~33.8 m, that is, the distance between the terminal fire control room and the sump is 19.2 m~33.8 m, which can basically ensure that the vapor concentration at the fire control room does not exceed the standard.

6. Calculation results and quantitative analysis of evaporation and diffusion in the sump

According to the heat radiation diffusion model of pool fire in the previous article, this section quantitatively studies the following contents:

(1) The quantitative relationship between the pool fire heat radiation and the equivalent diameter of the sump, and the distance between the fire control room and the sump; The main and secondary factors affecting the heat radiation are given through correlation analysis.

(2) Quantitative analysis shall meet the conditions that the equivalent diameter of the sump and the distance between the fire control room and the sump should meet when the thermal radiation intensity at the fire control room (not more than 9000W/m²) is met.

Natural gas combustion heat ΔH_c is 50MJ/kg; Air density ρ_0 is 1.29kg/m³. First, calculate the flame surface heat flux q_0 with formula 8. Using formula 18, the ratio h of flame height to diameter (equivalent diameter of the sump) is obtained. Use formula 16 and formula 17 to obtain intermediate variables a and b . Then substitute the above calculation results into Formula 10~Formula 15 to obtain the intermediate variables A, B, J, K, V_H, V_V . Then substitute the calculated intermediate variable into formula 9 to obtain the view factor V . Finally, according to formula 7, the thermal radiation value of the fire control room at the wharf is calculated, as shown in Figure 6 and Figure 7.

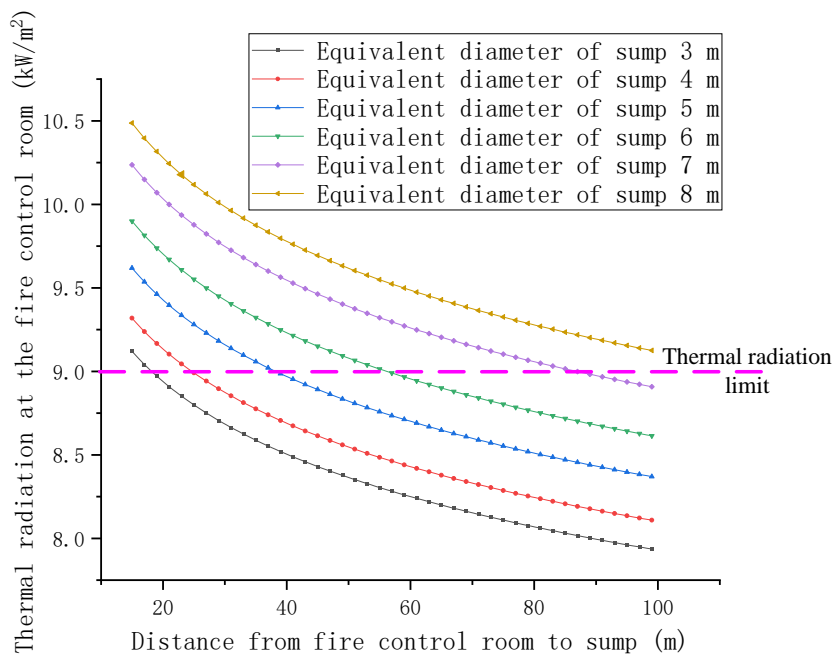


Fig. 6 Relationship between the amount of heat radiation received by the fire control room and its distance to the sump

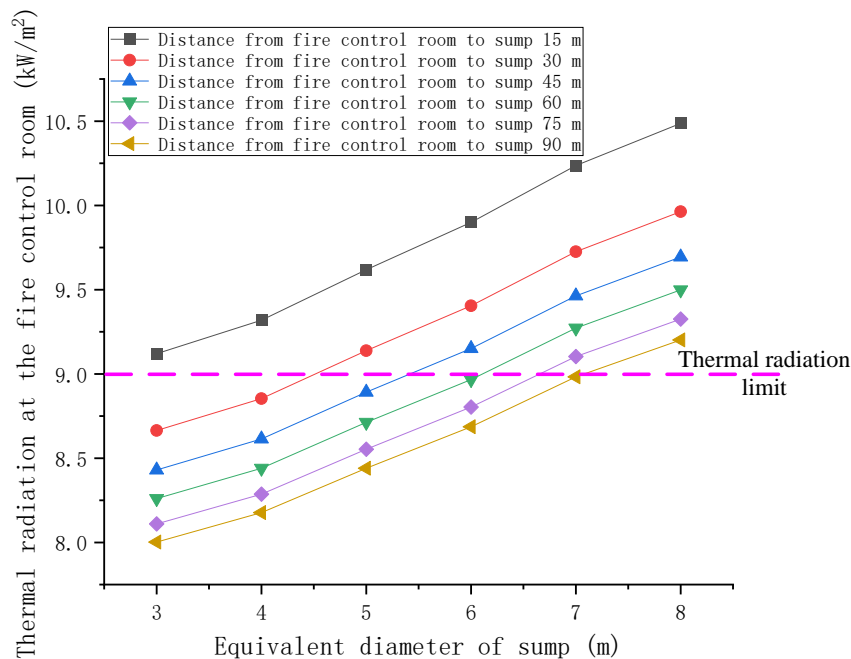


Fig. 7 Relationship between the amount of heat radiation received by the fire control room and the equivalent diameter of the sump

The calculation results are analyzed as follows:

(1) It can be seen from Figure 6 that the thermal radiation at the fire control room is inversely proportional to the distance from the fire control room to the sump, and this inversely proportional relationship is roughly negative logarithmic. It can be seen from Figure 7 that the thermal radiation at the fire control room is in direct proportion to the equivalent diameter of the sump, and the direct proportion is approximately linear.

(2) Further, the correlation coefficients between the thermal radiation at the fire control room and its distance to the sump and the equivalent diameter of the sump are -0.64 and 0.94, respectively. The correlation between the thermal radiation and the equivalent diameter of the sump is stronger. In the design of the wharf, the thermal radiation intensity at the fire control room can be controlled preferentially by adjusting the equivalent diameter of the sump.

(3) It can be seen from Figure 6 that when the equivalent diameter of the terminal sump exceeds 7m, the distance from the fire control room to the sump needs to be more than 90m to meet the thermal radiation limit requirements of the fire control room; This distance requires that it is easy to limit the location of the sump or fire control room. It is recommended that the equivalent diameter of the sump should not exceed 7m during design.

(4) It can also be seen from Figure 7 that when the distance between the fire control room and the sump is less than 15m, the thermal radiation value at the fire control room exceeds the specified limit value regardless of reducing the opening area of the sump. Therefore, the distance between the fire control room of the wharf and the sump should not be less than 15m.

7. Summary

The size design and location setting of the sump of the LNG terminal are the core issues in the design of the LNG terminal, and also relate to the safe production of the terminal. At present, the theoretical research is still lack of pertinence and comprehensiveness, the engineering practice is lack of theoretical basis, and the design scheme is difficult to distinguish. Based on the theory of evaporation diffusion and pool fire heat radiation in the terminal sump, this paper gives a detailed modeling process and calculation method, and applies it to engineering practice, and draws the following research conclusions:

(1) The impact of strong wind on the vapor diffusion in the terminal sump is dual, which can dilute the vapor concentration and increase the influence range of the vapor. In the design, the impact of wind speed on the vapor diffusion concentration needs to be determined through quantitative calculation.

(2) The steam concentration and thermal radiation value at the fire control room of the wharf are strongly related to the equivalent diameter of the sump and the distance from the fire control room to the sump. However, the distance from the fire control room to the sump has a stronger correlation with the steam concentration, and the equivalent diameter of the sump has a stronger correlation with the thermal radiation. In order to meet the restrictive requirements at the fire control room, the corresponding variable values can be adjusted preferentially during design.

In addition, this paper also gives specific calculation results and quantitative conclusions, which can provide reference for the design and safety evaluation of the terminal sump.

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