ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

Risk assessment of pool fire accident for inland river LNG powered ships

Yuhang Tang [a], Yong Chang [b] and Jingxuan Wang [c]

School of shanghai, maritime University, Shanghai 201306, China.

[a]694121821@qq.com, [b]1378560785@qq.com, [c]1796088316@qq.com

Abstract

faced with the crisis of global warming and climate deterioration, LNG ships can effectively reduce the impact on the environment and climate. In the era of energy saving, emission reduction, environmental protection and sustainable development, LNG ships have become the darling of China's inland waterway shipping industry. However, according to the chemical and physical properties of LNG, it is still one of the dangerous chemicals. The possibility of accident is inevitable, and once the accident happens, the harm will be great. Therefore, it is necessary to evaluate the accident risk of China's inland river LNG powered ships. In this paper, by establishing the corresponding model and risk assessment, the size of the threat range of relevant accidents will be visually displayed on the map.

Keywords

LNG; Pool fire; Risk assessment; Safe shipping.

1. Introduction

In 2009, Sandia national laboratory, funded by the U.S. department of energy, conducted two LNG leaks and pool fires. During the experiment, LNG is continuously discharged into the center of a 120m diameter (maximum depth 6m) tank and ignited by an igniter in the center of the tank. The first experiment generated a 20m diameter pool fire. In order to generate a larger pool fire, the second experiment released 260m cubed LNG within 2min, with a peak mass flow of more than 1600kg/s and an average flow of more than 802kg/s. The fire did not extend to the windward edge of the LNG pool, only covering about 50% of the total leakage area. In addition, compared with previous experiments, the second experiment produced relatively less smoke, and the ratio of flame height to diameter was significantly higher than that of previous field experiments.

In 2018, Zhang et al. conducted on-site tests of LNG pond fire in a rectangular concrete pit (6.4m*10m) at the Breton fire training site in the United States. In this work, the mass combustion rate of LNG was measured by the thermocouple method to be 0.186km/ m3. Due to the large wind speed and scale of the test site, the mass combustion rate of the measured LNG liquid pool on land was the highest so far. The study determined several key parameters of large-scale LNG pool fire, including mass combustion rate, flame geometry, flame velocity field and thermal radiation.

2. Theoretical model and analysis of LNG leakage pool fire

A pool fire occurs when flammable liquid in a pool is ignited and burns directly on the pool. Assuming that the pool is round, uniformly thick, and horizontal, the solid flame model is used to calculate the thermal radiation from the pool fire, and to calculate the dynamic area and volume of the pool based on the fuel leaking out of the tank or pipe valve. The flames rising from the pool fire form a tilted cylinder, and the radiation generated on the surface of the cylinder is calculated based on the rate of

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

combustion, the height of the flame, the tilt Angle, and the radiation from the surface of the flame. The thermal energy incident on the target object is the product of the thermal radiation energy flux on the surface of the flame, the coefficient of geometric perspective and the transmittance of atmospheric thermal radiation.

2.1 Heat radiation energy flux

The method of Moorhouse and Pritchard was used to estimate the average heat radiation energy flux per unit area on the surface of the cylinder, and the calculation formula was as follows:

$$E=\frac{f_{rad}\Delta h_c\dot{m}}{\left(1+4\frac{h}{d}\right)}$$

In the formula: h ——flame length (m);

d ——The diameter of the pool (m);

Δh_c ——burning calories $(\mathrm{J\cdot kg^{-1}})$;

$\dot{m}$ ——Mass combustion rate per unit area $(\mathrm{kg\cdot m^{-2}\cdot s^{-1}})$;

f_{rad} ——Part of the heat radiation releases energy, and the radiation energy coefficient is a constant 30%

Where, the mass combustion rate per unit area is calculated by the ratio of combustion and evaporation heat, and the calculation formula for temperature correction is as follows:

$$\dot{m}=0.001\cdot\frac{\Delta h_c}{\Delta h_v+c_p\left(T_b-T\right)}$$

In the formula: c_p —— specific heat capacity $(\mathrm{J\cdot kg^{-1}\cdot K^{-1}})$;

T_b ——Ambient boiling temperature (K);

Δh_v ——heat of evaporation $(\mathrm{J\cdot kg^{-1}})$;

T ——The temperature of the pool (K).

2.2 Geometric Angle coefficient

The pool fire flame is assumed to be a dense cylinder of flame that intersects in a circle with a plane parallel to the ground,order $u^*=u\cdot\left(\frac{\rho_a}{g\cdot\dot{m}\cdot d}\right)^{\frac{1}{3}}$ is the dimensionless wind speed defined,The calculation formula for the flame height of pool fire is as follows:

$$h=d\cdot 55\cdot\left(\frac{\dot{m}}{\rho_a\cdot\sqrt{g\cdot d}}\right)^{0.67}\cdot\left(u^*\right)^{-0.21}$$

In the formula: ρ_a ——Ambient air density $(\mathrm{kg\cdot m^{-3}})$;

The tilt Angle of pool fire flame is:

When $u^*\le 1$, $\theta=0$;

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

When $u^{*}>1$, $\theta=\cos^{-1}\frac{1}{\sqrt{u^{*}}}$

Geometric Angle coefficient which is definded by Sparrow and Cess is:

$$dF_{A_j-dA_i}=\frac{dA_i}{A_j}\int_{A_j}\frac{\cos\beta_i\cos\beta_j dA_j}{\pi r^2}$$

In the formula: A_j——The area of the radiating surface;

dA_i——Accepts the area of the object;

β_i——The Angle between the normal of the target and the straight line from the target to the radiating surface;

β_j——The Angle between the normal line at a point on the radiating surface and the line from that point to the target;

r——The distance between a point on the radiating surface and a target.

For radiant surface area A_i and the target area dA_i, order $q'=$ theintensity of incident radiation per unit area, $E'=$ radiant power per unit area,therefore:

$$q'=\frac{q}{dA_i}=\frac{E\bullet F\bullet\tau}{dA_i}=\frac{E'\bullet A_j\bullet F\bullet\tau}{dA_i}=E'\left(\frac{A_j}{dA_i}F\right)\tau$$

By dividing the surface of the flame, the integral is calculated, and the integrand is evaluated at the center of each partition, and these values are combined to produce an estimate of the integral.For three orthogonal orientations of the object, the geometric Angle coefficients are obtained f_1,f_2 and f_3,Then, the maximum geometric view Angle coefficient (in all directions on the surface of the target object) is calculated as follows:

$$f=\sqrt{f_1^2+f_2^2+f_3^2}$$

2.3 Liquid pool dynamics

For tank leakage, Bernoulli equation is used $Q_T(t)(kg\bullet s^{-1})$,that is, the liquid mass flow rate from the leakage hole is:

$$Q_T(t)=C_{dis}A_f\sqrt{2(P_h-P_a)\rho_l}$$

In the formula: C_{dis}——discharge coefficient (0.61);

A_f——flow area (m^2);

P_h——The liquid pressure in the liquid at the height of the leak hole;

P_a——ambient atmosphere pressure (Pa);

ρ_l——The density of the liquid in the tank $(kg\bullet m^{-3})$

Where, the flow area A_f depends on whether the liquid surface intersects with the leakage hole, and the flow area is:

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

$$A_f(t)=\begin{cases} A_h & \text{The liquid level is above the leak hole} \\ A_h\left(\dfrac{h_l}{\zeta_h}\right) & \text{The liquid level intersects the leak hole} \end{cases}$$

In the formula: h_l——The height of the liquid above the bottom of the leak hole(m)

ζ_h——Hole height or diameter (m),Depending on whether the hole is rectangular or circular.

When the leakage hole is located below the liquid surface, the pressure at the leakage hole, that is, the sum of the pressure in the gas gap at the top of the tank and the pressure above the bottom of the liquid column, is calculated as follows:

$$P_h(t)=\begin{cases} e_{cs}+h_l\rho_l g & \text{The liquid level is above the leak hole} \\ p_a+h_l\rho_l g & \text{The liquid level intersects the leak hole} \end{cases}$$

Where, e_{cs} is the saturated vapor pressure of the chemical (Pa).

With the continuous leakage time, the pressure in the tank keeps decreasing, the liquid evaporates into the gas phase space and the temperature change caused by evaporative cooling. The new temperature and saturated vapor pressure of the vapor in the gas phase space are recalculated. At the same time, as the height of the liquid above the bottom of the leak hole decreases, the pressure at the leak hole decreases continuously until it is finally equal to the atmospheric pressure. According to the physical model, the mathematical model of the leak is calculated from the fuel leak to the stop, and then until the air enters the storage tank.

If the fuel leak burns faster than the liquid pool, the liquid pool will continuously expand and expand around under the influence of gravity. The liquid pool is approximately uniform in thickness and temperature, and the radius of the liquid pool r_p changes as follows:

$$\frac{dr_p}{dt}=\frac{1}{r_p}\sqrt{\frac{2gm_p}{\pi\rho_l}}$$

In the formula: m_p——Dynamic mass of the pool

g——gravitational acceleration

r_p——The radius of the pool

ρ_l——The density of the liquid in the pool

If the thickness of the liquid pool is less than 0.5 cm, the liquid pool will stop expanding and the area of the liquid pool will remain unchanged until the liquid is completely burned.

3. Simulation of LNG pool fire accident

3.1 Introduction to simulation software

ALOHA is a hazard analysis and quantitative risk assessment simulation software used to simulate the release of chemicals and the spread of toxic clouds after release, as well as various fire and explosion scenarios, providing estimates of the spatial range of hazards associated with accidental release of volatile and flammable chemicals. These include breathing in toxic chemical vapors,

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

thermal radiation from chemical fires and pressure waves from steam cloud explosions that affect human health.

ALOHA uses a graphical interface for data entry and results to show possible exposure to toxic vapors, gas clouds. Areas of explosive overpressure or fire radiation from the vapor cloud are graphically represented as threat areas. ALOHA can produce simulation results of resultant forces and give the results fast enough to give decision-makers a reasonably accurate reference in a real emergency. ALOHA contains the physical properties of more than 1,000 common hazardous chemicals, and users can edit and add multi-component hazardous chemicals, such as liquefied natural gas. The main features of ALOHA are summarized as follows:

（1）generate the output of various specific schemes, including regional threat map, threat map at specific locations and source strength map;

（2）calculate the rate of leakage of chemicals from storage tanks, liquid pools or pipelines, and predict the change of release rate with time;

（3）simulate various release scenarios: toxic gas cloud, BLEVE, jet fire, steam cloud explosion and pool fire;

（4）Assess different types of threats: toxicity, flammability, thermal radiation, overpressure;

simulate the leakage of chemicals into water.

3.2 Modeling idea and process of LNG pool fire based on ALOHA

Step 1: create location information (latitude and longitude, altitude, time difference, etc.). The location information can be used to determine and analyze the distribution of buildings and people around the accident, and the local geographic information can be effectively analyzed.

Step 2: determine the time of the accident and judge the time point of the accident by time, which can provide reference for searching for information of solar altitude and solar radiation;

Step 3: the major constituent of LNG is Methane. Select the corresponding chemical Methane as the major constituent of LNG fuel, input the information of the proportion of each LNG group into the software, and construct the physical and chemical properties of the LNG mixture.

Step 4: determine the information of atmosphere and surface roughness (including wind speed, wind direction, surface roughness, atmospheric cloud coverage, atmospheric temperature, atmospheric stability level, relative humidity, etc.), and the meteorological information will have a great impact on the accident.

Step 5: establish the real situation of LNG tank source model (including tank geometry size, shape, LNG fuel state and temperature, and LNG fuel capacity) to ensure the authenticity and accuracy of the simulation;

Step 6: build the pool fire model. After the LNG power vessel tank leaks, the liquid tank will be formed and ignited to form the pool fire.

Step 7: select the dangerous situation simulation of the accident (including toxic area, flammable area, explosion area, etc.), select the simulation of each scene (including ignition time, ignition type, blockage level, etc.);

Step 8: to establish a focus on horizontal LOC isoline limit, such as isoline concentration limit, thermal contour limit, limit information such as the overpressure isoline (including toxic levels of attention, the attention of the overpressure focus, inflammable, thermal radiation levels), so as to create for accident threat area estimation, assessment of accident influence scope, damage degree, etc.;

Step 9: set additional information, such as personnel, buildings, other vessels, etc., to further ensure the authenticity of the accident;

Step 10: check the above steps and output if there are no errors.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

3.3 Pool fire accident risk assessment

To enhance the risk comparison of hazards under different climatic conditions, three different climatic conditions were selected for assessment.

(1) the first group of simulation

parameters	numerical value
coordinate	Pudong new area, Shanghai, altitude 0m, east longitude 121 °29 '47 ", north latitude 31 °14' 35"
time	2018-12-07-12:00
chemical substances	Liquefied natural gas LNG
weather	Northwest wind, wind speed 4 (6m/s), light rain, atmospheric temperature 8°C, air humidity 60%
Situation of tank	Horizontal, diameter 1.454m, volume 5m cubed, temperature -150°C, filling coefficient 0.9
Leak hole	Rectangle, 3cm long, 2cm wide, 30cm from bottom of tank

The above information is the first group of simulation information, and the following results can be obtained by input the numerical value:

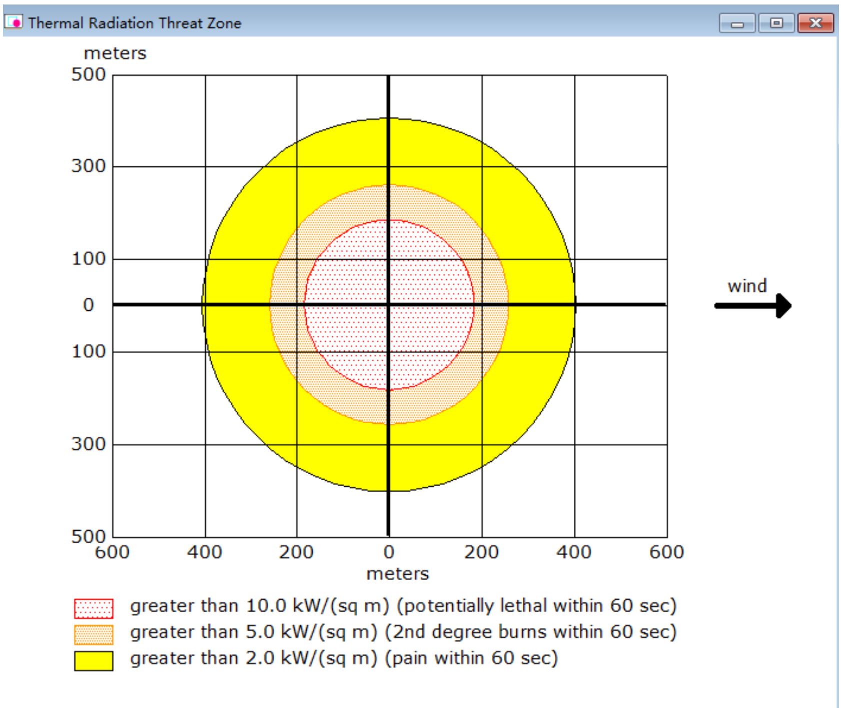

Figure 1.first group

The following results can be obtained by analyzing the above figure:

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

Area	Threat to size(kW/m²)	Range parameter(m)	hazard rating
red zone	＞10	360	dead zone
orange zone	＞5	500	Seriously injured zone
yellow zone	＞2	810	Minor zone

Second group of simulations

parameters	numerical value
coordinate	Pudong new area, Shanghai, altitude 0m, east longitude 121 °29 '47 ", north latitude 31 °14' 35"
time	2019-05-22-12:00
chemical substances	Liquefied natural gas LNG
weather	Northwest wind, wind speed 1 class (1m/s), clear, atmospheric temperature 30℃, air humidity 65%
Situation of tank	Horizontal, diameter 1.454m, volume 5m cubed, temperature -150℃, filling coefficient 0.9
Leak hole	Rectangle, 3cm long, 2cm wide, 30cm from bottom of tank

The above information is the second group of simulation information, and the following results can be obtained by entering the numerical value:

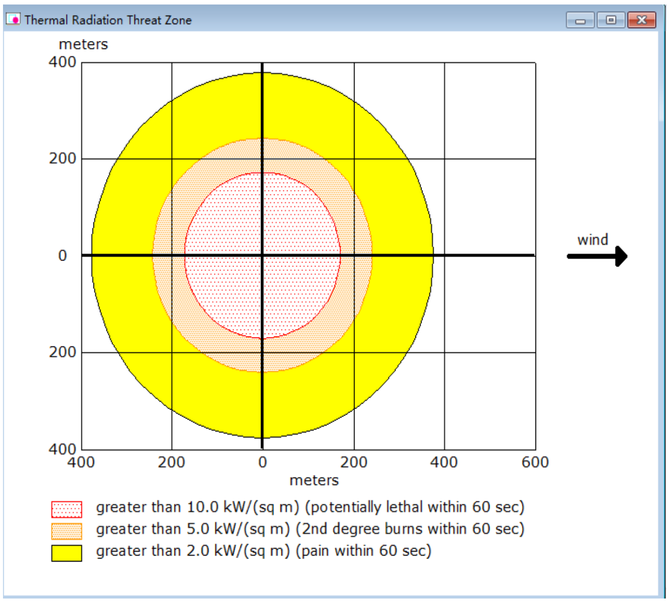

Figure 2.secend group

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

The following results can be obtained by analyzing the above figure:

Area	Threat to size(kW/m^2)	Range parameter(m)	hazard rating
red zone	>10	340	dead zone
orange zone	>5	470	Seriously injured zone
yellow zone	>2	780	Minor zone

Third group of simulations

parameters	numerical value
coordinate	Pudong new area, Shanghai, altitude 0m, east longitude 121 °29 '47 ", north latitude 31 °14' 35"
time	2019-10-29-12:00
chemical substances	Liquefied natural gas LNG
weather	Northwest wind, wind speed 4 class (6m/s), clear, atmospheric temperature 20°C, air humidity 60%
Situation of tank	Horizontal, diameter 1.454m, volume 5m cubed, temperature -150°C, filling coefficient 0.9
Leak hole	Rectangle, 3cm long, 2cm wide, 30cm from bottom of tank

The above information is the third group of simulation information, and the numerical input results are as follows:

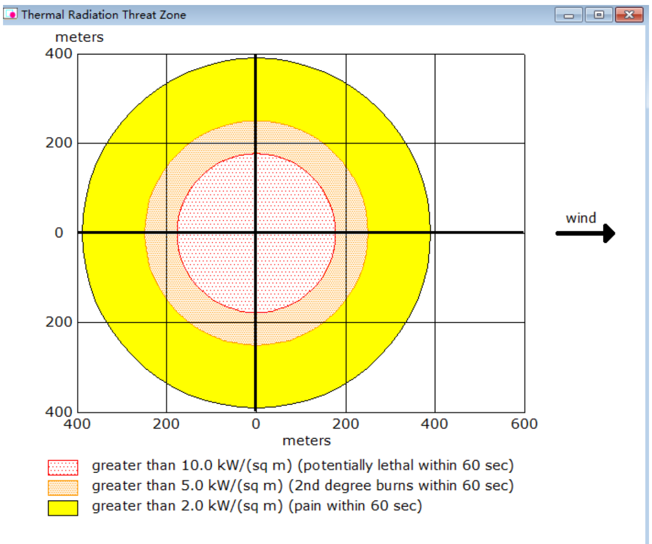

Figure 3.third group

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

The following results can be obtained by analyzing the above figure:

Area	Threat to size**(kW/m^2)**	Range parameter**(m)**	hazard rating
red zone	＞10	360	dead zone
orange zone	＞5	480	Seriously injured zone
yellow zone	＞2	790	Minor zone

schematic diagram of combustion rate of pool fire and variation of thermal radiation

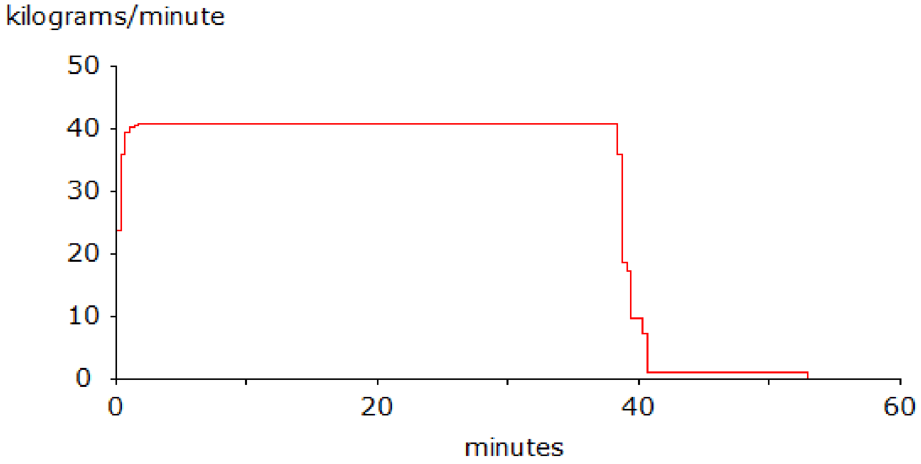

Figure 4.Diagram of combustion rate of LNG liquid pool fire

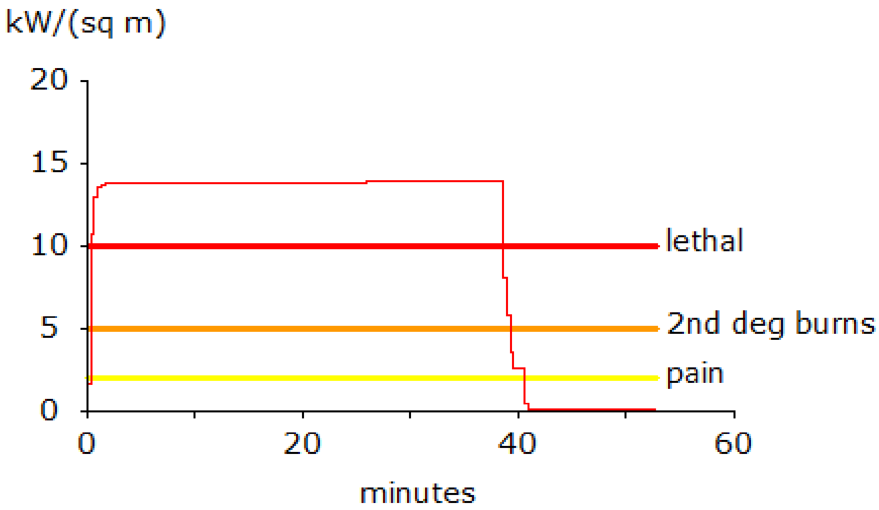

Figure 5.Schematic diagram of thermal radiation variation 10 meters away from the downwind direction of the liquid pool center

(5)Three groups of simulation comparison summary

Through pairwise comparison and joint comparison of three groups, we can find that: wind speed, atmospheric cloud cover, temperature will have a certain impact on the damage range of pool fire. The influence of temperature on wind speed and cloud cover is relatively large. Wind speed has a relatively small effect on atmospheric cloud cover and temperature. Generally speaking, the external

ISSN: 2414-1895 DOI: 10.6919/ICJE.202001_6(1).0037

meteorological environment will have a certain impact on the damage scope of pool fire, but the impact is not very big.

It can be seen from the schematic diagram of the combustion rate of pool fire and the variation of thermal radiation that the combustion rate of pool fire basically synchronizes with the variation of thermal radiation. Two minutes before the accident, the combustion rate can be from 0 to 40.7 kilograms/min, thermal radiation will soar from 0 to 13.7 kw/(sq m). Starting from 38 minutes, the value of the two will decrease rapidly, approaching to 0 in 41 minutes and completely becoming 0 in 53 minutes. That means the entire pool fire accident lasted about 53 minutes.

4. Conclusion

Although the research on LNG safety has achieved fruitful results, there are still many research directions that need to be further developed. The main disaster of LNG leakage accident is the thermal radiation of pool fire. This paper simulates the analysis of pool fire disaster under different weather conditions for reference. The following problems still need to be solved around the safety of LNG pool fire:

(1) Due to the limitations of safety and site, it is difficult for LNG pool fire to be carried out indoors and outdoor environment will be damaged. Therefore, due to various restrictions, the mechanism of pool fire fire still needs to be further explored.

(2) The study of LNG pool fire in irregular liquid pools is still blank.

(3) High-power foam is very effective for the protection of LNG, but the research on the physical mechanism of the foam is not perfect. It is necessary to establish a high-power foam protection model for LNG, and further study the physical protection process of high-power foam.

References

[1] Thoman DC, O'Kula KR, LAUL J C, et al. Comparison of ALOHA and EPI code for safety analysis applications[J]. Journal of Chemical Health and Safety, 2006, 13(6): 20-33.

[2] EPA, NOAA. ALOHA user manual [M/OL]. [2007- 05-08]http: //www. epa. gov/OEM /cameo /aloha. Htm

[3] Babrauskas V.Estimating large pool fire burning rates[J].Fire Safety Technology,1983,19(4):251-261

[4] Moorhouse J.Scaling Laws for Pool Fires Determined From Large Scale Experiments[J].IChemE Symposium Series,1982,71:165-179

[5] DEPAＲTMENT OF TＲANSPOＲTATION. Cabrillo port liquefiednatural gas deepwater port license application ［N］. Federal Ｒegister,2007.

[6] GOPALASWAMI N,KAKOSIMOS K,ZHANG B,et al.Experimental and numerical study of liquefied natural gas (LNG)pool spreading and vaporization on water［J］.Journal of HazardousMaterials,2017,334: 244.