Quantitative Evaluation for Consequences of LNG Releases Based on RBI

Xin Ma, Tonghui Shi[a]

School of Mechatronic Engineering, Southwest Petroleum University, Chengdu 610500, China

[a]837772412@qq.com

Abstract

LNG demand is increasing dramatically year by year, and the related equipment is the important hazardous source. In the event of releases, the consequence is usually the fire and explosion, and it will pose a potential threat to the safety of the people. Therefore quantitative evaluation for consequences of LNG releases is very important to risk management of LNG equipment, because it can set up the corresponding safety distance. On account of the representative fluid C1~C2 didn't consider the pool fire consequences in API581 consequences calculation model. But the pool fire consequence is the main accident consequence in consequences of LNG releases. Therefore, this study provides a new quantitative evaluation model for consequences of LNG releases based on RBI, and the consequence areas of pool fire, jet flame, flash fire, BLEVE fireballs and VCES are calculated respectively. Then it compares this model and the API581 consequences calculation model by a real case. Finally, the analysis of the calculation results is done and the rationality and practicability of this model are verified.

Keywords

RBI; LNG releases; quantitative evaluation; risk management; explosion.

1. Introduction

LNG (Liquefied Natural Gas, LNG for short) is a clean, efficient energy use LNG can improve the environment, reduce haze, so our country is constantly increasing among natural gas in primary energy ratio. At present, China LNG industry has begun to take shape, the number of annual imports of LNG has reached millions of tons, by 2020, China's coastal areas import LNG scale up 6000 ×104t (the equivalent of natural gas 827.4 ×108m^3) [1].

LNG receiving station, LNG, LNG ship, LNG vehicles around the world, even including some remote areas.In the event of LNG leakage, will pose a potential threat to the safety of the people.According to the physical properties of LNG and LNG leakage, low temperature combustion explosion happens after major harm some harm, smothering action, such as cold explosion phenomenon.Leakage may be many reasons, consequences of leakage is various, therefore to establish a reasonable LNG leakage consequences of quantitative calculation model to predict the consequences of leakage is very important.

2. The RBI leak consequences of quantitative evaluation method

Risk-based Inspection method (RBI) is Based on Risk analysis, Based on the inherent in the system or potential danger and its consequences for the qualitative or quantitative evaluation, on the basis of through formulating the plan of targeted testing of equipment for testing and maintenance.

LNG leakage equipment failure consequences can generally from the spill area, burning explosion equipment damage and casualties caused by the influence area, equipment repairs, shutdown caused by the direct and indirect economic losses, etc. In addition must also consider some influencing factors, such as: the degree of impact on the environment, the influence degree of the credibility of the enterprise, etc. The economic loss due to equipment repair costs, production can estimate by using the method of expert evaluation, is relatively easy to estimate, therefore focuses on equipment damage area and casualties consequences area calculation.

The ultimate consequence area according to formula (1):

$$A = \max(A_e, A_t) \quad (1)$$

In the formula: A is the final consequence area (m^2), A_e is the area for equipment damage caused by burning explosion consequences (m^2), A_i is the area for casualties consequences (m^2).

Casualties consequences area can be calculated by formula (2):

$$A_i = \max(A_i^f, A_i^t) \quad (2)$$

In the formula: A_i^f is the burning explosion casualties caused by area(m^2), A_i^t is the toxicity of the casualties caused by the consequences of the medium leaking area(m^2).

The RBI leak consequences quantitative calculation flow chart shown in figure 1:

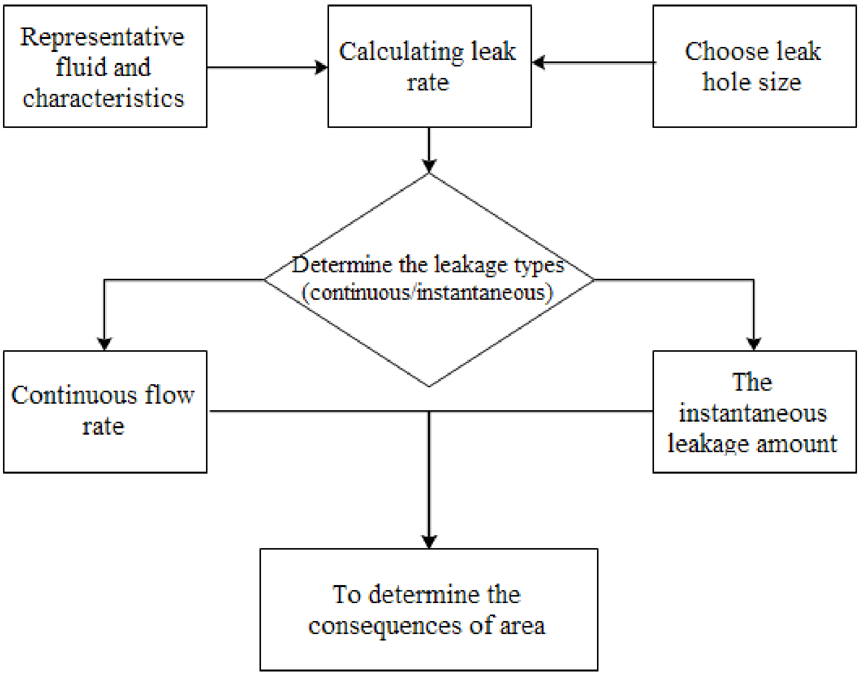

Fig.1 The flow chart of quantitative calculation of releases consequences based on RBI

3. LNG leakage consequences quantitative evaluation model based on RBI

3.1 LNG leakage consequence analysis

LNG leakage will cause low temperature to human body anesthesia and suffocate. Without adequate protection measures, the person is in less than 10 ℃ after waiting for long, will have the risk of anesthesia in low temperature, physiological function and mental activity as the temperature drops are falling, heart function failure, fell further will die. Although LNG steam not poison, but the oxygen content is low, easy to make the person suffocate. If inhaled pure LNG steam and not quickly off, will soon be loss of consciousness, and death in a few minutes. Usually, the oxygen minimum standard of 10% is not a permanent damage human body. Corresponding to the normal air contains 52.4% of methane, the oxygen content is 10% [2].

52.4% explosion limit of methane concentration is greater than 15%, by a formula (2) the toxicity of LNG leakage casualties consequences area can not consider the consequences.

Due to the leakage situation, lighting, combined with the surrounding environment situation and situation of LNG diffusion, LNG leaking combustible consequences may include: flash fire, pool fire, jet fire, BLEVE fireballs and VCES combustion and other different situation. After the leakage accident process analysis is shown in figure 2.

3.2 The choice of physical parameters of LNG leakage and aperture

Consult API581 logistics database [3], LNG representative fluid is C1 ~ C2.LNG liquid mixture of methane, the density of methane density as the standard state of more than 600 times, more storage under normal pressure and critical pressure (4.6 MPa), the boiling point is about -162 ℃, explosion limit of 5% ~ 15%.

According to the API581 recommended by a group of aperture (6.25 mm, 25.4 mm, 6.25 mm diameter and container) leak rate calculation and consequence area respectively.

3.3 calculating leakage rate and determine the leakage types

Because of liquefied natural gas (LNG) is a kind of superheated liquid suddenly evaporate when liquid leakage, will appear the phenomenon of gas liquid two phase flow at this time.But direct evaporation of the liquid fraction was very small (about 3%), so the leakage of liquefied natural gas (LNG) speed can be calculated by liquid.API581 of liquid leakage rate computation formula is as follows:

$$Q_L = C_d \cdot A_k \sqrt{\frac{2g \cdot 144p}{\rho}} \tag{3}$$

In the formula: Q_L is liquid discharge rate (kg/s); C_d is the discharge coefficient, 0.61; A_k is the orifice area (m^2); ρ is liquid density, 450 kg/m^3; $p$is for container pressure difference between pressure and atmospheric pressure (Pa); g is acceleration of gravity, 9.8 m/s2 .

For LNG leakage problem, because the LNG storage of atmospheric pressure, the pressure in the container between the atmospheric pressure and the general pressure to zero.The LNG leakage rate can be calculated according to the formula:

$$Q_L = C_d \cdot A_k \sqrt{\frac{2p}{\rho} + 2gh} \tag{4}$$

In the formula: h is liquid level height (m) above the orifice.

Fluid leakage, and according to the size of the leak hole and leak rate of the formula is a continuous leakage or instantaneous leakage. Generally all the "holes" (less than 6.25 mm in diameter) simulation for continuous leakage; For other formulas of pore size, when leakage 4540 kg takes less than 3 min, through a given pore size of the leakage of instantaneous leakage, all lower leakage rate of the simulation for continuous leakage[4].

3.4 equipment damage and casualties area calculation

LNG leakage consequences to consider the atmospheric temperature, relative humidity, wind speed and the influence of the weather conditions such as the stability, the complicated calculation.API581 standards, therefore, gives the simplified calculation formula of combustible consequences [3], as shown in table 1.

Table 1 Formulas of consequence areas of LNG releases

Leakage types	Equipment damage area (A_e/m^2)	Casualties area (A_i/m^2)
Continue to leak	$A_e = 8.67x^{0.98}$	$A_i = 21.83x^{0.96}$
Instantaneous leakage	$A_e = 6.46X^{0.67}$	$A_i = 12.46X^{0.67}$

Note: x is leak rate, kg/s; X is total leakage, kg.

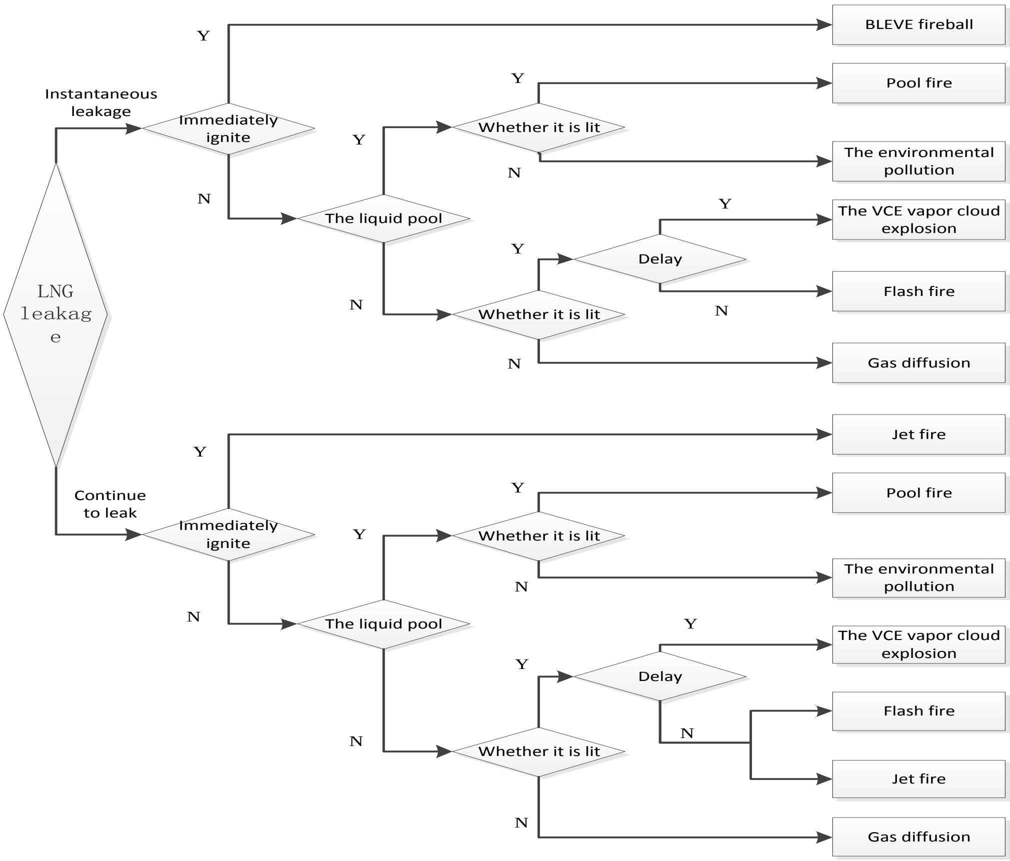

Fig.2 The flow chart of LNG accident consequences

In this paper, combined with the conditions of LNG leakage consequences according to the pool fire, jet fire, ignite, BLEVE fireballs and VCES leak burning consequences calculated results area respectively, and then according to the specific events of API581 probability to calculate the comprehensive area.

3.4.1 Pool area fire aftermath

LNG leakage flow to the ground after the formation of incomplete gasification liquid pool, pool will form after being lit the fire [5].Pool fire burning velocity can be expressed as [6]:

$$\frac{dm}{dt} = \frac{0.001H_c}{H} \tag{5}$$

In the formula: dm/dt unit surface area is combustion rate (kg/(m^2 s)); H_c is the heat of combustion of liquid, J/kg; H is the heat of vaporization of liquid, take 1.22 J/kg.

Liquid pool assumed to be the round pool, flame height calculated by formula (6) [6] :

$$h = 84r\left[\frac{dm/dt}{\rho_a(2gr^{0.5})}\right]^{0.6} \tag{6}$$

In the formula: h is flame height (m);r is liquid pools radius (m); ρ_a is the surrounding air density, 1.17 kg /m^3.

Release of the burning liquid pool total thermal radiation flux is[6] :

$$Q = (\pi r^2 + 2\pi r)\frac{dm}{dt}\cdot\eta\cdot H_c / \left[72(\frac{dm}{dt})^{0.61} + 1\right] \tag{7}$$

In the formula: Q is the thermal radiation flux (W); η is the efficiency factor, take 0.35.

Assume that all heat energy from the liquid pool center of radiation,it is from the liquid pool center x radiation intensity for:

$$I = \frac{Qt_c}{4\pi x^2} \tag{8}$$

In the formula: I is thermal radiation intensity (W/m^2). t_c is heat conduction coefficient, t_c is preferable in the absence of a relatively ideal data 1;x is the target point to the liquid pool center distance (m).

According to the provisions of API581, equipment damage of thermal radiation standard is 37615(W/m^2), more than all equipment will be damaged;Standard for the thermal radiation deaths in the 12538(W/m^2), when more than will lead to death.

The pool fire fire equipment damage area and the area of the casualties can be respectively as follows:

$$A_{e1} = \frac{Qt_c}{4I_e} \tag{9}$$

$$A_{i1} = \frac{Qt_c}{4I_i} \tag{10}$$

3.4.2 The effects of jet fire area of product

Combustible matter continues to leak the jet formation, the leakage in the mouth when the light will form a jet fire. According to the formula (11) calculation point heat source heat value [7]:

$$q = \eta Q_L H_c \tag{11}$$

In the formula: q is point heat source thermal radiation flux (W); η is the efficiency factor, 0.35.

On the jet axis point heat source to the distance of the thermal radiation intensity of x point formula is:

$$I = \frac{qR}{4\pi x^2} \tag{12}$$

Equipment can be obtained when the radiation intensity is $I_e = 37615(W/m^2)$ the damage area of:

$$A_{e2} = \frac{\eta Q_L H_c R}{4I_e} \tag{13}$$

When the radiation intensity is $I_i = 12538(W/m^2)$ available casualties for the area:

$$A_{i2} = \frac{\eta Q_L H_c R}{4I_i} \tag{14}$$

3.4.3 The consequences of flash fire area

Flash fire is combustible gas or steam leak into the air and mixes with the light of a kind of explosive combustion process. Flash fire is one of the shortest duration formula, the burning speed, the whole process is instantaneous. So in this paper, we consider that flash fires burn in the fire occurred outside the scope of radiation damage is very small, to ignore it, only consider LNG leakage within the scope of thermal radiation.

So the assumption that occurred after the flash of fire area is the LNG diffusion of inflammable and explosive area. In this paper, with the spread of heavy gas clouds box model.

Assume that leakage of LNG heavy gas clouds of the initial volume, so:

$$V_o = m / \rho_o \tag{15}$$

Assume that the initial radius of air mass height is general, the initial radius for [8]:

$$R_o = \left(\frac{2m}{\pi \rho_o} \right)^{\frac{1}{3}} \tag{16}$$

At any time with the downwind distance change of the concentration of heavy gas clouds is [9]:

$$C = C_o \left(x / V_o^{\frac{1}{3}} \right)^{-1.5} \tag{17}$$

Leakage after the accident, in the process of transmission due to the motion of the wind, the influence of terrain, the spread of heavy gas clouds trajectory for oscillation, the band of the external sector is the hazard area. Fan-shaped spread Angle generally take 40 °, but the real damage area is much smaller, which is about a 12 °Angle band area, the area is [9]:

$$S = \frac{\pi D^2}{8} + 1.2xD + 0.15x^2 \tag{18}$$

According to the criteria, for equipment damage, flash fire ignition in the area of the lower flammable limit range 25% as the rule of impact; Flash fire ignition for casualties, with 100% of the lower flammable limit range when as a rule of influence. LNG limit is 5% ~ 15% in average burning in the air, the lower explosive limit by 5%, when the concentration of the gas is 0.0375 kg/m^3.

To 25% of the surface of the lower flammable limit within the scope of influence as criteria, the flash fire equipment damage consequence area is:

$$A_{e3} = \frac{\pi D^2}{32} + 0.3xD + 0.0375x^2 \tag{19}$$

To 100% of the surface of the lower flammable limit within the scope of influence as criteria, the flash fire fire casualties consequences area is:

$$A_{i3} = \frac{\pi D^2}{8} + 1.2xD + 0.15x^2 \tag{20}$$

3.4.4 BLEVE fireballs consequences of an area

BLEVE fire by fire baking is refers to the LNG container, such as external impact caused by the container is damaged, causing a large number of hot gas released into the air.Encounter fire will produce severe burning ball of fire.The radius of the ball can be calculated by formula (16) [10]

$$R = 2.665M^{0.327} \tag{21}$$

The fireball duration [10]:

$$t = 1.089M^{0.327} \tag{22}$$

Fireball radiation heat flux from the burning of as follows:

$$Q = \frac{\eta H_c M}{t} \tag{23}$$

Distances from the center of the fire intensity of thermal radiation effects of x point formula is:

$$I = \frac{QT_c}{4I_e} \tag{24}$$

When the fire disaster, the equipment damage area and the area of the casualties can be respectively is:

$$A_{e4} = \frac{QT_c}{4I_e} \tag{25}$$

$$A_{i4} = \frac{QT_c}{4I_i} \tag{26}$$

3.4.5 VCES area of vapor cloud explosion consequences

As the LNG is a superheated liquid, so suddenly evaporate when liquid leakage and vapor cloud formation, if rapid accumulation vapor cloud explosion limit and achieve, meet fire after VCES vapor cloud explosion will occur. Vapor cloud explosion possibility is extremely high and the harmful consequences of great form. LNG leakage lead to belong to the open space of the explosion, the explosion pressure container storage means that the explosion of the potential energy of LNG. Usually this potential explosion energy use TNT equivalent said, can be calculated by formula:

$$W_T = \frac{1.8AMH_c}{Q_T} \tag{27}$$

Application rule of overpressure, in the shock wave overpressure may according to the formula [11]:

$$\Delta P = 0.137Z^{-3} + 0.119Z^{-2} + 0.269Z^{-1} - 0.019 \tag{28}$$

$$Z = x\left(\frac{P_o}{W_T Q_T}\right)^{1/3} \tag{29}$$

Under the effect of shock wave equipment secondary damage radius calculation formula is as follows [11]:

$$R = \frac{KW_T^{1/3}}{\left[1+(3175/W_T)^2\right]^{1/6}} \tag{30}$$

When the vapor cloud explosion, the equipment damage area is:

$$A_{e5} = \pi R^2 \tag{31}$$

Personnel under the effect of shock wave of the eardrum rupture probability is 0.01 the blast wave peak overpressure is = 17000 pa, the casualties area can be obtained as follows:

$$A_{i5} = \frac{\pi Z^2}{(P_o / W_T Q_T)^{2/3}} \tag{32}$$

3.4.6 Comprehensive consequences area

Comprehensive consequences area computation formula is as follows:

$$A = P_1 \cdot A_1 + P_2 \cdot A_2 + \cdots\cdots + P_i \cdot A_i \tag{33}$$

Check API581 [3], the probability of a specific event in form of LNG continuous leakage and instantaneous spill fire probability is 0.2.Combined with the LNG flow chart of accident consequence, it is concluded that special event probability as shown in table 2.

Table 2 Probabilities of specific events

Leakage ways	The probability of all kinds of results				
	Pool fire	Jet fire	Flash fire	BLEVE	VCES
Continuous leakage	0.032	0.144	0.008		0.016
Instantaneous leakage	0.032		0.016	0.132	0.016

4. The instance

Taking a 50 m^3 LPG station device prizing formula LNG horizontal tank as an example, its design pressure is 1.2 MPa, inner diameter is 2850 mm, Ø external pressure for the standard atmospheric pressure. Select leakage aperture is 25.4 mm, is located in the axis of storage tank, and assume that liquid pools radius of pool fire is 5 m.

Leak rate calculated by the formula (4) $Q_L = 9.765kg/s$,the simulation is continuous leaking.API581 consequences model and LNG leakage model calculation results as shown in table 3.

Table 3 Calculation results of consequences model

Consequence model	Equipment damage area	Casualties area

		/m2	/m2
API581 consequences model		80.9	194.6
LNG leakage model of the consequences	Pool fire	2992.3	8977.3
	Jet fire	254.4	763.2
	Flash fire	7083	28331.8
	BLEVE	1880898.6	5642845.7
	VCES	15777.8	72139.7
	comprehensive	441.5	1778.1

5. Conclusion

(1) For LNG leakage accident, this paper proposes a new model, use case analysis, several major consequence of LNG leakage: pool fire, jet fire, ignite, BLEVE and VCES respectively conducted a quantitative calculation. On the basis of analyzing the cause of the accident, and combining the API581 probability of a particular event, comprehensive consequences area are obtained.

(2) It can be seen from table 3, the LNG leakage consequences model to calculate the equipment damage area and the area of the casualties were greater than by API581 consequences model calculation results. This is because the API581 consequences model, for the representative fluid medium to a final state of C1 ~ C2 for gas, and does not take into account the pool fire fire consequences, but the consequence of LNG leakage, as the main pool fire accident consequences. Therefore, this model is more suitable for the calculation of LNG leakage consequences.

(3) LNG is more and more widely used, once the leak will affect people's life and property safety. By means of quantitative evaluation, LNG leakage consequences can set out the corresponding safe distance, the related equipment for LNG risk management and planning is of great significance.

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