Construction of Safety Risk Management Platform for Storage Tank Concentration Zone in the Port Area

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Abstract: In this paper, the evolution process of the fire and explosion accidents was analyzed according to the safety risk factors of the harbor storage tank. The fire and explosion accident models were established, and a storage and pipeline management platform were developed consisted of functions of information sharing, risk warning, and emergency treatment in terms of fire and explosion accidents.

Keywords: Harbor safety, Storage tank, Management platform, Fire and explosive emergency

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1. INTRODUCTION

The Yangtze River is a vital channel and water catchment area for regions along it to coordinate the development of the economy, with over 400 water intakes for residents' living and industry use. With the development of economy, a huge amount of storage tanks filled with oil and other flammable and explosive chemicals have been placed along the river, which could cause fire and explosion accidents, triggering domino effects.

Fire and explosion accidents can cause serious disruption in social order and local environment. For example, the Buncefield fire was a major conflagration caused by a series of explosions in 11 December 2005 at the Hertfordshire Oil Storage Terminal, in Hertfordshire, England[1]. The terminal was the fifth largest oil-products storage depot in the United Kingdom, with a capacity of about 60 million imperial gallons (270 ml) of fuel. The first and largest explosion led to further explosions which eventually overwhelmed 20 large storage tanks. The explosion was induced by a fuel-air explosion in a vapor cloud of evaporated leaking fuel. The impact of the fire was significant: hundreds of homes were evacuated, and about 2,000 people had to find alternative accommodation; the motor ways were closed for 29 km, and some aircrafts were only allowed 40% of the fuel they normally take on board due to the lack of oil; moreover, business disruption and groundwater pollution last for a long time in local area.

Since the 1860s, theories and experiments of combustion, such as single tank and tank leakage combustion ignited by the pool fire and jet fire have been proposed by the research institutions and universities in developed countries including United States and Japan. Many experimental data and models of relationship between the combustion mechanisms and the radiant characteristics were presented[2]. In 1984, the Federal Institute for Materials Research and Testing conducted a combustion experiment on three LPG storage tanks containing 50% propane with no insulation[3]. Thomas[4], Brotz[5] and Heskestad[6] deduced a series of empirical equations of columniform flame to the flame height of the pool fire, respectively. They explored the influence of flame geometry and size on the flux value and propagation law of the thermal radiation, as well as the failure criterion and the hazard analysis of fire.

The management system set in the storage tank concentration zone in the domestic port is not perfect. Thus, we constructed a safety risk management platform for the storage tank concentration zone in the port area in this paper. The platform shared information in the database among the cooperative units such as the dangerous chemicals, satellite images, and the emergency plans. It provided real-time monitoring and history data recording for the storage tanks and pipelines, and could send alert in abnormal condition. Moreover, it also provided the functions of accident simulation and emergency treatment, model optimization of the population evacuation and the resource allocation in the fire and explosion accidents.

2. FIRE AND EXPLOSION RISK IN THE STORAGE TANK CONCENTRATION

Fire and explosion tend to accompany in the accidents caused by flammable and combustible chemicals. The LPG, for example, would flash after the leakage from the storage tank, and forms a gas cloud mixed with droplets. The generated gas cloud mixed with air would lose its momentum effected by ground and environment, disperse following the dominant wind direction and finally lead to a UVCE (unconfined vapor cloud explosion) by the static electricity ignition. If the gas cloud is not diluted by air, it could meet open fires and cause BLEVE (boiling liquid expanding vapor explosion). The evolution law is just like **Fig. 1**.

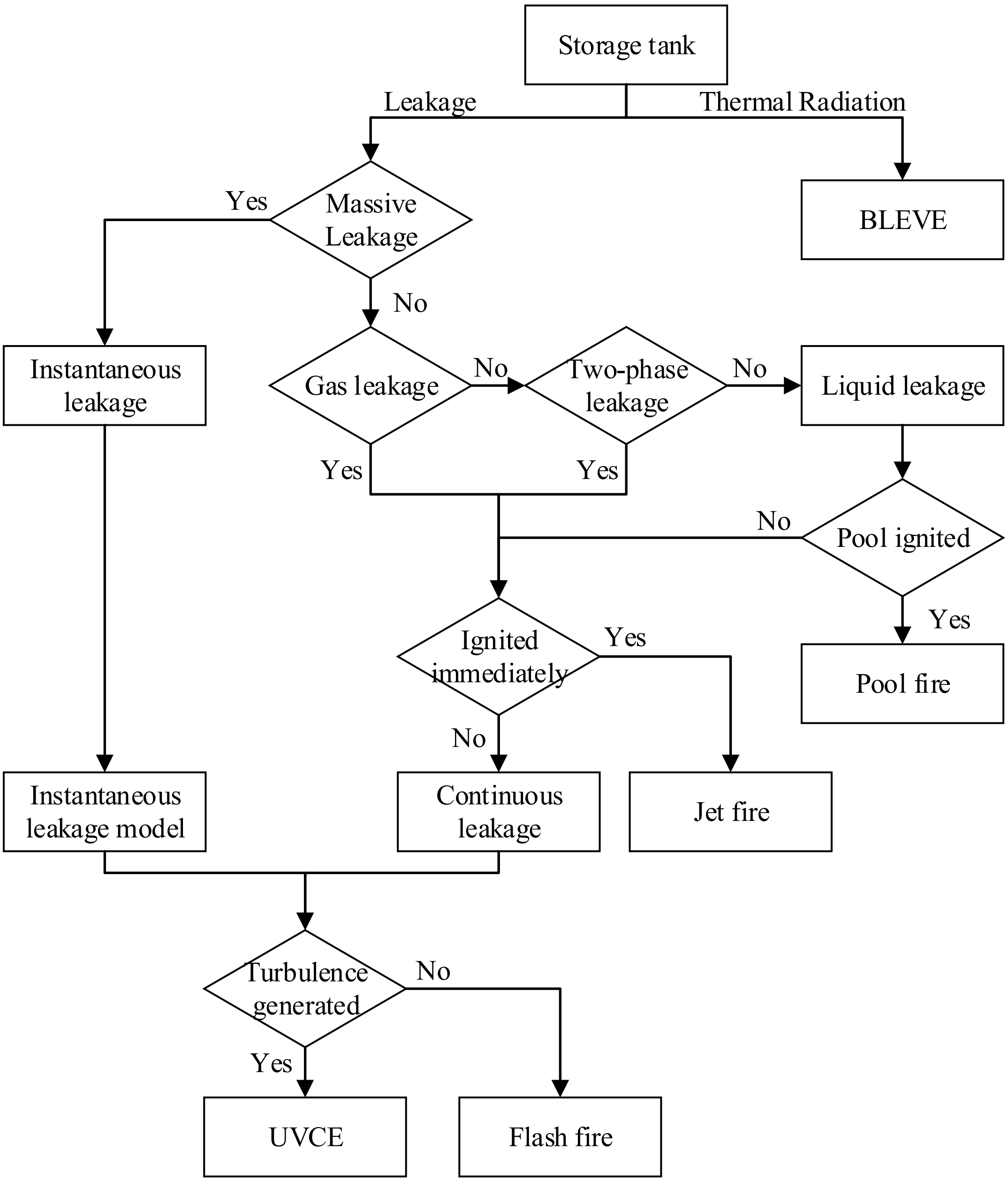


Fig. 1: Evolution Law of Fire and Explosion Accidents

2.1. Fire Accident Model

Fire accidents generated by leakage of the flammable and combustible gas or liquid often take place in the storage tank concentration. According to different modes of combustion, the fire could be classified into pool fire, jet fire, fire ball, and flash fire[7]. The models of pool fire and jet fire are written in Section 2.1.1 and 2.1.2, respectively. The intensity of thermal radiation is one of the most important parameters[8].

2.1.1. Pool Fire

When the flammable liquid is released, it would flow to the ground forming a liquid pool or flow to the surface covering the water surface. If the liquid pool is ignited by an ignition source, the pool fire will be formed.

If the boiling point is higher than the environment temperature, the combustion rate per unit area could be described by Eq.(1):

$$\frac{\mathrm{d}m}{\mathrm{d}t}=\frac{0.001H_c}{C_p(T_b-T_0)+H} \tag{1}$$

Where, $\frac{\mathrm{d}m}{\mathrm{d}t}$ represents the burning velocity per unit, kg/(m^{2}s); H_c is the heat of combustion, J/kg; C_p is the specific heat at constant pressure, J/(kg·K); T_b is the boiling point, K; T_0 is the environment temperature, K; H is the heat of vaporization, J.

However, the boiling point of some kinds of gas such as pressurized liquefied gas and the frozen liquefied gas is lower than the environment temperature. In this condition, the combustion rate per unit area could be presented in Eq.(2):

$$\frac{\mathrm{d}m}{\mathrm{d}t}=\frac{0.001H_c}{H} \tag{2}$$

By assuming the edge of the pool surface is a circle, the flux of heat release Q could be written as follows:

$$Q=(\pi r^2+2\pi rh)\frac{\mathrm{d}m}{\mathrm{d}t}\eta H_c\left[\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)^{0.61}+1\right] \tag{3}$$

where r is the radius of the pool, m; h is the height of the flame, m; η is the efficiency factor, which could be selected from 0.15 to 0.35.

The height of the flame is represented in Eq.(4):

$$h=84\cdot r^{\left(\frac{\frac{\mathrm{d}m}{\mathrm{d}t}}{\rho_0\sqrt{2gr}}\right)^{0.6}} \tag{4}$$

where p_0 is the ambient air density, kg/m^3; g is the gravitational acceleration and usually set to 9.8 m/s^2.

Suppose that all of the thermal radiation comes from a tiny sphere at the center of the pool and then we can calculate the intensity of the thermal radiation by Eq.(5):

$$I = \frac{Qt_c}{4\pi x^2} \tag{5}$$

where Q is the total flux of heat radiation, W; t_c is the heat conductivity of the air; x is the distance between the calculation point and the center of the pool.

2.1.2. Jet Fire

The jet formed by the leakage of pressurized gas could be ignited, which would lead to a jet fire. In the calculation of heat flux, the jet fire could be treated as a series of point heat source located at the axis of the jet. The flux of thermal radiation Q at each point heat source is shown in Eq.(6):

$$Q = \eta Q_0 H_c \tag{6}$$

where η is the efficiency factor, which could be selected as 0.35; Q_0 is the efficiency velocity, kg/s; H_c is the heat of combustion, J/kg.

The flame length of jet fire is considered as the jet axis length from the leakage crack to the lower combustion limit of the flammable mixed gas. The intensity of thermal radiation is written as Eq.(7) to simplify the calculation:

$$I_j = \frac{Rq}{4\pi x^2} \tag{7}$$

where R is the radiation rate, selected as 0.2; q is the radiation flux of the point heat source, W; x is the distance between the calculation point and the point heat source.

The total thermal radiation flux of the jet fire is represented by the sum of that at each point heat source shown in Eq.(8):

$$I = \sum_{j=1}^{n} I_j \tag{8}$$

where n is the number of point heat sources, which is often set to 5.

2.2. Explosion Accident Model

Explosion is a sudden release of energy with high pressure and able to cause huge disruptions. Common explosion accidents include VCE (vapor cloud explosion), BLEVE (boiling liquid expanding vapor explosion) [9], and physical explosion.

2.2.1. Energy of Physical Explosion

The explosion of pressure vessel acted by the internal medium pressure is a physical explosion. The explosion energy is calculated by different formula according to different internal media phase of the pressure vessel.

The released explosion energy is calculated by Eq.(9) for gas media:

$$E = \frac{pV}{10(\gamma - 1)} \left[1 - \left(\frac{10^5}{p} \right)^{\frac{\gamma - 1}{\gamma}} \right] \tag{9}$$

where p means the pressure of the internal media in the vessel, Pa; V means the volume of the vessel, m^3; γ means the heat capacity ratio.

If the internal media is pressurized or liquefied gas, the released explosion energy is described by Eq.(10):

$$E = \frac{\Delta p^2 V \beta}{2} \tag{10}$$

where Δp means the pressure difference before and after the explosion, Pa; V means the volume of the vessel, m^3; β means the coefficient of compressibility, Pa^{-1}.

If the internal media is liquefied gas, the physical processes consist of both the rapid expansion of gas and rapid evaporation of liquid. In the overheat condition, the explosion energy released from the crack of the vessel could be calculated by Eq.(11):

$$E = [(H_1 - H_2) - (S_1 - S_2)T_1]W \tag{11}$$

where H_1 means the enthalpy of the liquefied gas before the explosion, kJ/kg; H_2 means the enthalpy of the saturated liquid gas at atmospheric pressure, kJ/kg; S_1 means the entropy of the liquefied gas before the explosion, kJ/kg; H_2 means the enthalpy of the saturated liquid gas at atmospheric pressure, kJ/kg; W means the mass of the saturated liquid gas, kg; T_1 means the boiling point of the media at atmospheric pressure, K.

After the vessel exploded, the energy of explosion transforms into the energy of shockwave, the kinetic energy of the fragment, and the residual energy of vessel deformation, which is expressed by the energy conservation shown in Eq.(12):

$$E = E_1 + E_2 + E_3 \tag{12}$$

where E_1 means the energy of shockwave, E_2 means the kinetic energy of the fragment, E_3 means the residual energy of vessel deformation. In some case, E_3 can be ignored and the ratio of E_1 to E_2 is set to 1/4 for brittle fracture, or 3/2 for plastic fracture.

2.2.2. Impact Scope of Shockwave

When explosion happens, the overpressure of the shockwave attenuates gradually with the shockwave propagation out from the explosion center. The impact scope of shockwave which is usually measured with the radius of the shockwave propagation represents the range where the overpressure of the shockwave is higher than a certain value .

The radius of the shockwave propagation caused by the explosion of the pressure vessel can be calculated by Eq.(13):

$$R = 0.022 r_1 E_1 + d/2 \tag{13}$$

where r_1 means the rate of change for the radius of the impact scope; E_1 means the energy of shockwave, J; d means the diameter of the vessel.

The radius of the shockwave propagation caused by VCE was suggested by TNO (Netherlands Organisation for Applied Science Research) in Eq.(14):

$$R = C_s (N \cdot E)^{1/3} \tag{14}$$

where E means the energy of explosion, J; N means the efficiency factor, the ratio of shockwave energy to total energy, which is usually selected to 10%; C_s means the empirical constant depending on the damage level and is listed in **Table 1**.

Table 1: Damage Level

Damage Level	C_s, mJ	Damage to Equipment	Damage to Person
1	0.03	Damage to structure and processing equipment	1% population die of lung damage; >50% eardrum broken; >50% hit by fragments
2	0.06	Restorable damage to structure surface	1% eardrum broken; 1% hit by fragments
3	0.15	Glass broken	Hit by broken glass
4	0.4	10% Glass broken	

2.2.3. Kinetic Energy and Penetration of Fragments

For the liquid internal media, the energy of fragments is too small to be considered; while if the internal media is gas or liquefied gas, the fragments would have a high enough kinetic energy to damage persons, equipment and buildings by penetration.

The initial velocity of the fragment produced by pressure vessel explosion is expressed by Eq.(15):

$$v_0 = \sqrt{\frac{2}{m_0} \cdot F \cdot \frac{\Delta p}{\gamma - 1} V} \tag{15}$$

where m_0 means the mass of the pressure vessel, kg; F means the yield factor of the fragment fracture energy; Δp means the pressure difference between before and after the explosion, Pa; γ means the heat capacity ratio; V means the gas volume in the vessel.

Considering the influence of air resistance, the velocity of the fragment at the flying distance as S is written as Eq.(16):

$$v = v_0 \exp\left(-\frac{A}{m} \rho_0 S \right) \tag{16}$$

where V_0 means the initial velocity of the fragment, m/s; C means the factor of air resistance; A means the area of the fragment, m^2; m means the mass of the fragment, kg; ρ_0 means the air density, kg/m^3; S means flying distance of the fragment, m.

The penetration depth of fragments to structures depends on the kinetic energy of fragments and the strength of structures, which can be calculated by Eq.(17):

$$X = K \cdot m^{n_1} v^{n_2} \tag{17}$$

where X means the penetration depth of fragments, m; m means mass of the fragment, kg; v means impact velocity of the fragment, m/s; K, n_1 and n_2 are parameters of the target, listed in **Table 2**.

Table 2: Penetration Parameters of Target

Material	*K*	n_1	n_2
Concrete (compressive strength: 35 N/m^2)	1.8×10^{-5}	0.4	1.5
Brick structure	2.3×10^{-5}	0.4	1.5
Mild Steel	0.6×10^{-5}	0.33	1.0

3. SAFETY RISK MANAGEMENT PLATFORM OF STORAGE TANK CONCENTRATION

In this paper, we constructed a safety risk management and emergency platform, which integrates the functionality of information sharing, intelligence monitoring, and emergency warning shown inas **Table 3**.

Table 3: Safety Risk Management and Emergency Platform

Subsystem	Element			
Standard Information Database	Underlying Database			
	Safety Risk Factors			
	Storage Tank and Pipeline Information			
Monitoring and Warning	Safety Risk Monitoring			
	Safety Risk Warning			
Emergency Management	Safety Risk Plan	Emergency Plan	Emergency Resource	Emergency Exercise
Aid Decision Making	Consequence Simulation	Decision Aid	Resource Scheduling	Personnel Evacuation

3.1. Information Sharing

The information sharing subsystem utilizes the Web Service technology on the Internet combined with the supervision department and the enterprises related to safety risk of hazardous cargo. The shared information consist of basic information of hazardous cargo, medical and agency, fire-fighting forces, emergency shelters, accident situations, and etc.

邻近企业名称	邻近企业性质	与临近企业距离	与临近企业距离与临近	备注
保税港务	物流	储罐与保税港务堆场距离20	储运设施与双山岛村居民住	已与保税港务有协议
中储粮仓储	仓储	长江国际5#罐区与中储粮仓	储运设施与双山岛村居民住	
长源热电厂	电力	储运设施与长源热电厂距离	储运设施与双山岛村居民住	
凯伦仓储	仓储	6#罐区与凯伦仓储罐区距离	储运设施与双山岛村居民住	
力凯仓储	仓储	7#罐区与力凯仓储距离最近	储运设施与双山岛村居民住	
开诚仓储	仓储	9#罐区与开诚距离最近处70	储运设施与双山岛村居民住	
东马油脂	仓储	9#罐区与东马油脂仓储距离	储运设施与双山岛村居民住	
华燕仓储	仓储	9#罐区与开诚距离最近处70	储运设施与双山岛村居民住	
瑞欣物流	物料	8#罐区与瑞欣物流距离70m	储运设施与双山岛村居民住	
舜天仓储	仓储	9#罐区与舜天仓储距离66m	储运设施与双山岛村居民住	

Fig 2: Basic Information of Enterprises with Hazardous Cargo

3.2. Warning and Monitoring of Hazard

This platform including the functions of data collection, data analysis and alert information generation can display the hazard storage tank and pipeline monitored visually in real time based on GIS (geographic information system).

3.2.1. Monitoring and Early Warning for Storage Tanks

In the monitoring and early warning subsystem, many sensors are located on work sites to collect key parameters of the environment where the storage tanks are concentrated, including liquid level, temperature, humidity, pressure, flow, and etc. The historical trend of the monitoring data is recorded in the hard disk at SCADA Node, while the real-time trend is recorded in the memory. The collected data is saved and transferred to LAN (local area network), achieving joint defense with different departments and enterprises.

The system records the attribution of each storage tank, including type, material, nominal volume (m^3), radius (m), height (m), cargo name, cargo density (kg/m^3), fill rate (%), designed pressure (MPa), working pressure (MPa), working temperature (℃), annual average time of use (h), tank spacing (m), and etc. Users are able to set the threshold values of the monitored data, and the alarm system would triggered when the data is beyond the threshold value. Then the storage tanks with abnormal data would be marked clearly on the map with red color.

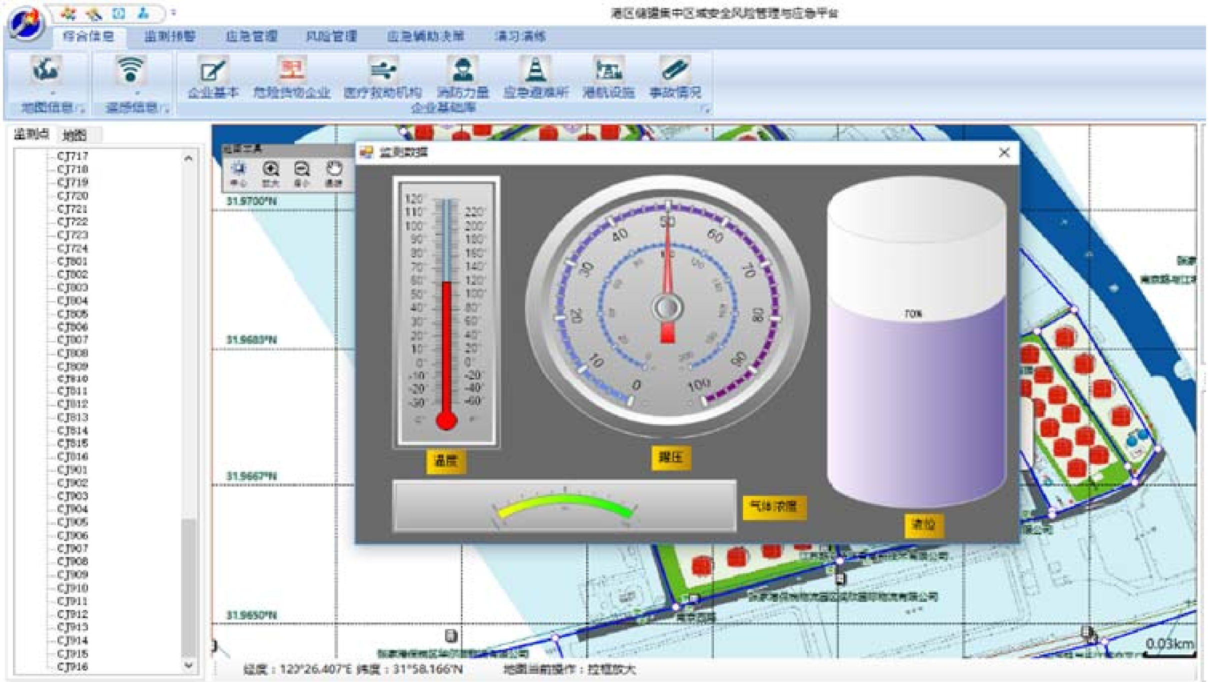
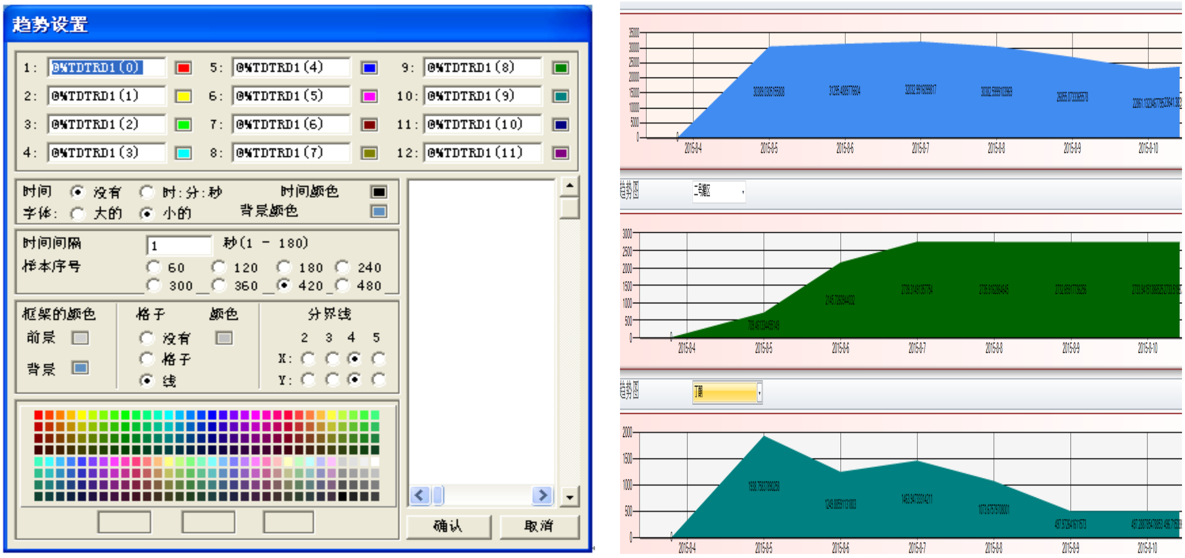


Fig. 3: Data Monitored in Real Time



1: @%TDTRD1(0)
2: @%TDTRD1(1)
3: @%TDTRD1(2)
4: @%TDTRD1(3)
5: @%TDTRD1(4)
6: @%TDTRD1(5)
7: @%TDTRD1(6)
8: @%TDTRD1(7)
9: @%TDTRD1(8)
10: @%TDTRD1(9)
11: @%TDTRD1(10)
12: @%TDTRD1(11)

时间 ● 没有 ○ 时:分:秒
字体: ○ 大的 ● 小的
时间间隔 1 秒(1 - 180)
样本序号 ○ 60 ○ 120 ○ 180 ○ 240 ○ 300 ○ 360 ● 420 ○ 480
框架的颜色 前景 背景
格子 ○ 没有 ○ 格子 ● 线 颜色
分界线 2 3 4 5
X: ○ ○ ● ○
Y: ○ ○ ● ○

Fig. 4: History Trend of Data Monitored

CJ916
气压：120.00
温度：30.00
气体浓度：50.0
液位：0.75

经度：120°27.023'E 纬度：31°57.999'N 地图当前操作：拉框放大

Fig. 5: Tanks with abnormal data are marked red

3.2.2. Video Surveillance in Real Time

The camera spots are listed on the map with red points, and clicking the red points is available for users to watch the scene of the cameras.

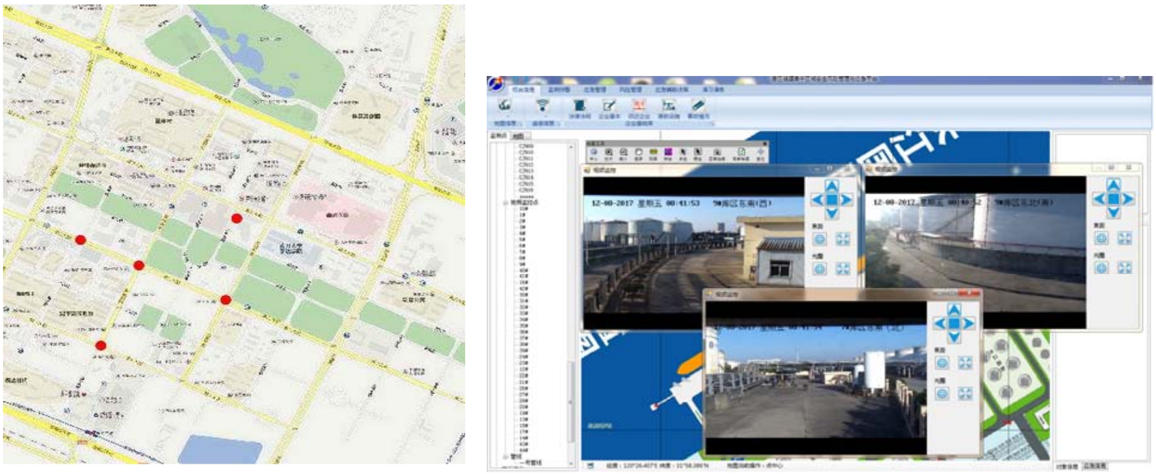
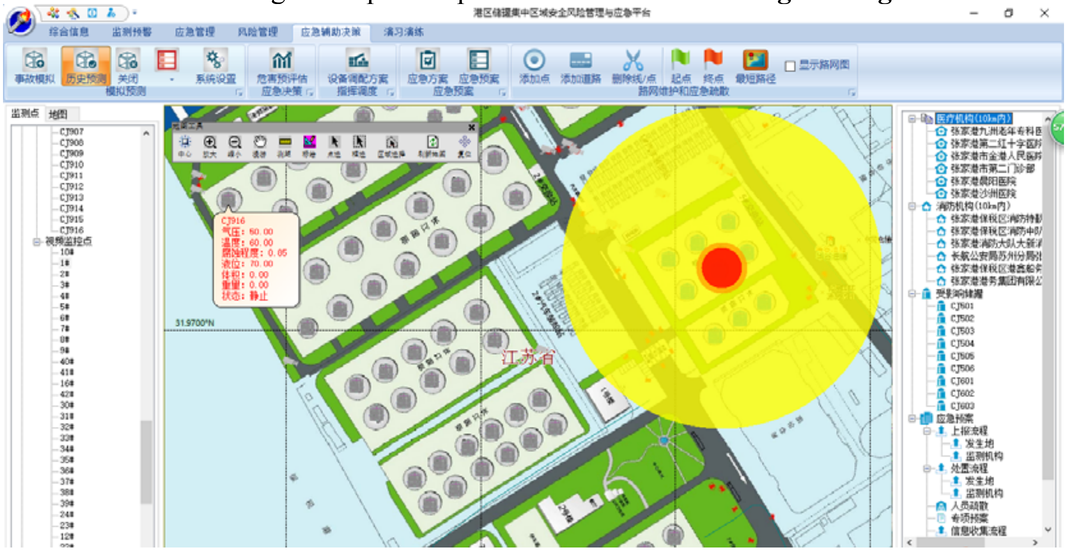


Fig. 5: Camera Spots on the Map; Scene from the Camera

3.3. Fire and Explosion Accident Simulation and Emergency

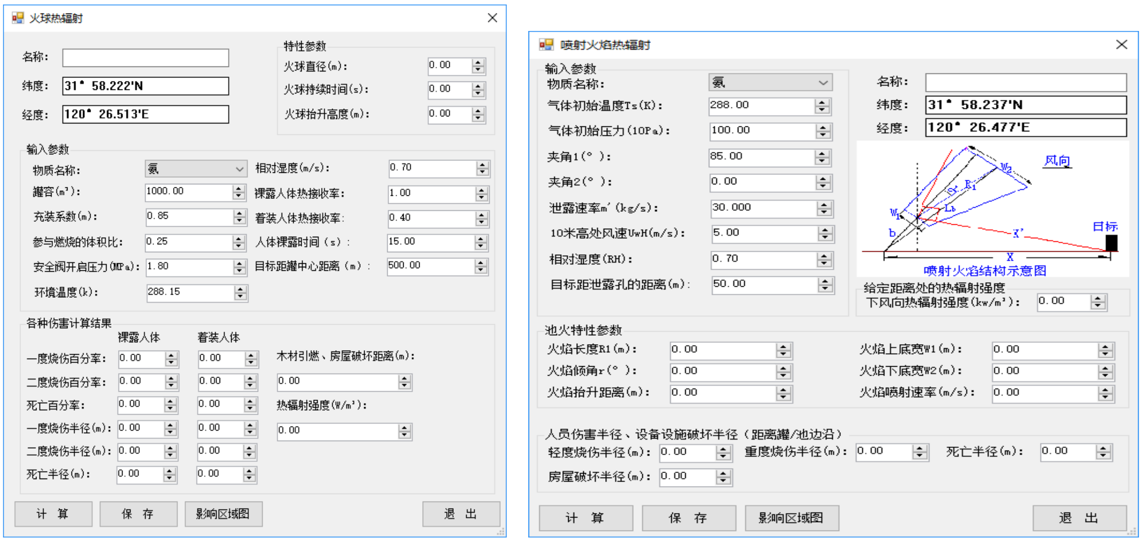
The emergency system, which could simulate and drill the fire and explosion accidents with numerical methods, is a important part of the platform.

In the platform, the semi-theoretical and semi-empirical models[10] are used to simulate fire and explosion disaster. The settings of important parameters are shown in **Fig. 6** ~ **Fig. 9** below.



CJ916
气压：60.00
温度：60.00
腐蚀程度：0.05
液位：70.00
体积：0.00
重量：0.00
状态：静止

Fig. 6: Thermal Radiation of Pool Fire



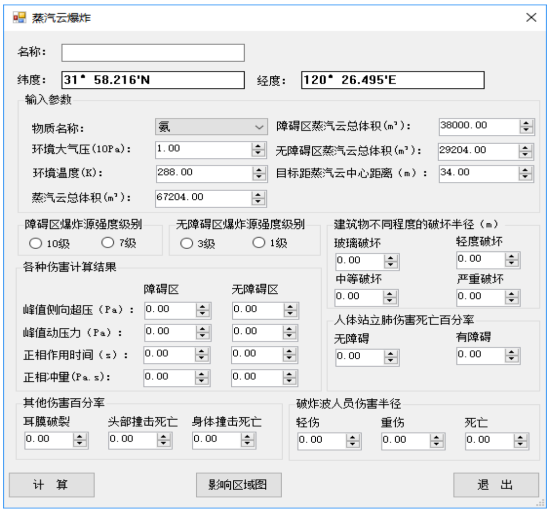
名称：
纬度：31° 58.222'N
经度：120° 26.513'E
火球直径(m)：0.00
火球持续时间(s)：0.00
火球抬升高度(m)：0.00
物质名称：氨
相对湿度(m/s)：0.70
罐容(m³)：1000.00
裸露人体热接收率：1.00
充装系数(m)：0.85
着装人体热接收率：0.40
参与燃烧的体积比：0.25
人体裸露时间（s）：15.00
安全阀开启压力(MPa)：1.80
目标距罐中心距离（m）：500.00
环境温度(k)：288.15

	裸露人体	着装人体
一度烧伤百分率：	0.00	0.00
二度烧伤百分率：	0.00	0.00
死亡百分率：	0.00	0.00
一度烧伤半径(m)：	0.00	0.00
二度烧伤半径(m)：	0.00	0.00
死亡半径(m)：	0.00	0.00

木材引燃、房屋破坏距离(m)：0.00
热辐射强度(W/m²)：0.00

物质名称：氨
气体初始温度Ts(K)：288.00
气体初始压力(10Pa)：100.00
夹角1(°)：85.00
夹角2(°)：0.00
泄露速率m′(kg/s)：30.000
10米高处风速UwH(m/s)：5.00
相对湿度(RH)：0.70
目标距泄露孔的距离(m)：50.00
名称：
纬度：31° 58.237'N
经度：120° 26.477'E
下风向热辐射强度(kw/m²)：0.00
火焰长度R1(m)：0.00
火焰上底宽W1(m)：0.00
火焰倾角r(°)：0.00
火焰下底宽W2(m)：0.00
火焰抬升距离(m)：0.00
火焰喷射速率(m/s)：0.00
轻度烧伤半径(m)：0.00
重度烧伤半径(m)：0.00
死亡半径(m)：0.00
房屋破坏半径(m)：0.00

Fig. 7: Thermal Radiation of Fire Ball and Jet Fire



名称：
纬度：31° 58.216'N
经度：120° 26.495'E
物质名称：氨
障碍区蒸汽云总体积(m³)：38000.00
环境大气压(10Pa)：1.00
无障碍区蒸汽云总体积(m³)：29204.00
环境温度(K)：288.00
目标距蒸汽云中心距离（m）：34.00
蒸汽云总体积(m³)：67204.00
障碍区爆炸源强度级别：○ 10级 ○ 7级
无障碍区爆炸源强度级别：○ 3级 ○ 1级

	障碍区	无障碍区
峰值侧向超压（Pa）：	0.00	0.00
峰值动压力（Pa）：	0.00	0.00
正相作用时间（s）：	0.00	0.00
正相冲量(Pa.s)：	0.00	0.00

玻璃破坏 0.00
轻度破坏 0.00
中等破坏 0.00
严重破坏 0.00
无障碍 0.00
有障碍 0.00
耳膜破裂 0.00
头部撞击死亡 0.00
身体撞击死亡 0.00
轻伤 0.00
重伤 0.00
死亡 0.00

Fig. 8: VCE parameter setting

4. CONCLUSION

To build the management platform of the storage tank concentration at the port, some summaries and analyses were performed to the evolution process of fire and explosion accidents induced by the leakage of chemicals. A series of semi-theoretical and semi-empirical models were established to simulate the fire and explosion accidents. The constructed platform consisted of functionality of information sharing, risk warning, and emergency simulation can be devoted to managing and forecasting the accidents occurring at the port in future.

References

[1] HSC and EA. Buncefield Major Incident Investigation, 2005
[2] Vemkatesh S, Ito A, Saito K. Flame Base Structure of Small-Scale Pool Fires. Combustion Science and Technology.1994,N01-3:37-62
[3] Droste B, Schoen W. Full scale fire tests with unprotected and thermal insulted LPG storage tanks. Journal of Hazardous Materials, 1988, 20 (1): 41-53
[4] Thomas P H. The Size of Flames from Natural Fires, 9th Symp. on Combustion. Academic Press Inc., London, 1963. 844

[5] Brotz W, Schonbucher A, Schable R. Statistical Inverstigations of Pool Flames, Int Loss Prevention Symp. , Basle, 1977

[6] Schneider V, Hofmann J. An Advanced Engineering Approach to Fire Simulation and Consequence Evaluation. Ed. by Kafka P and Wolf J, Elsevier, 1993. 499~510

[7] Reidel D, Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, a Pilot Study, a Report to the Rijnmond Public Authority, Dordrecht, 1982

[8] L T Cowley, A D Johnson. Oil and gas fires characteristics and impact, OTI92596, London: HSE. 1992

[9] J. E. S. Venart, G. A. Rutledge, K. Sumathipala, K. Sollows. To BLEVE or not to BLEVE: Anatomy of a boiling liquid expanding vapor explosion, Process Safety Progress, 1993, 12(2)

[10] YANG Jun-tao, WEI Dong. Selection and Analysis of Fire Models Based on Oil Tank Fire Simulation. China Safety Science Journal, 2004(01):31-36+3