Petrochemical plant multi-objective and multi-stage fire emergency management technology system based on the fire risk prediction

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Abstract

In accordance with the characteristics of petrochemical plant which has the complex process and gathered flammable and explosive materials, the fire risk evolution and prediction method and the strategy of fire hazard protection layer for petrochemical plant process and apparatus were put forward by the analysis of fire hazards distribution and characteristics of disasters accidents. Based on the fire risk prediction analysis, according to the layer of protection to the dangerous in the plant, the multi-objective and multi-stage emergency management system was brought forth aiming at the different stages of routine operation, potential fire accidents monitoring and elimination, fire accidents prediction and pre-warning, early disposal and emergency response. Using the advanced information technologies (GIS geographic information system, RS remote sensing and telemetry systems, etc.), integrating the different functions of risk assessment, monitoring and supervising, forecast and early warning, dynamic decision-making, comprehensive coordination, emergency response, optimize decision-making and so on, the emergency management system can help the petrochemical enterprises to realize dynamic security fire risk management, thereby enhancing the fire safety management of the petrochemical companies and fire prevention technology.

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1. Introduction

Petroleum chemical process is completed mainly through a series of physical, chemical reaction, and its main raw materials and products are in liquid and gaseous components which are almost toxic, flammable and corrosive. The production process often involves high temperature and pressure (or low temperature and pressure) and other complex technical operation, which the reactions are complex and strong continuity. Due to material transportation spilling, accidental ignition, reaction conditions out-of-control, operator maloperation and other reasons, during oil and chemical process in the production, it is possible to occur the high risk of fire and explosion accidents, which often accompanied with fire after the explosion, recrudescence and three-dimensional, large area, multi-point and other forms of combustion that could easily lead to heavy casualties and property loss and environmental damage. In recent years, petrochemical enterprises fire and explosion accidents in China have shown overall upward trend and the situation continued to be severe. Such as the "11.13" fire and explosion accident in Jilin Petrochemical Company of double benzene factory in 2005, not only caused heavy casualties and property losses, but also generated a large area of the Songhua River water pollution which have caused adverse effects in the whole country and the international community [1]. On January 7th 2010, PetroChina Lanzhou Petrochemical Company’s No.316 tank farm fire and explosion accident resulted in around eleven tanks serial exploding one after another, causing 12 casualties [2]. On July 16th 2010, Dalian Dagushan pipeline explosion and fire in PetroChina

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oil depot, resulted in a large number of oil spills and the formation of nearly 60000 square meters of floor flowing fire area, and triggered the tank farm No.103 tank fire, leading to a large area water pollution near Dalian sea Area [3]. In order to avoid serious and major fire & explosion accidents, ensure the safety production, reduce fire & explosion hazard degree, a series of chemical fire & explosion hazard analysis & evaluation methods and a more perfect HSE (Health, Safety and Environment) safety management system based on risk management were developed. Emergency management as one important link of HSE safety management system mainly involves in hazard identification, risk analysis, consequence assessment, emergency response, disaster recovery and disposal. In recent years, with the rapid development of information and network technology, based on GIS, RS and other information and network communication technology, the emergency response systems in the field of public safety have been widely developed and applied [4-6]. Such as the accidents early warning and emergency system established on the Geographic Information Systems (GIS) can not only meet the needs of early warning and emergency response command, but also improve the scientific emergency response, rational and intelligent level and optimize emergency response decision-making, operating procedures and emergency measures in short period of time. The current GIS-based decision support system of emergency has been widely used in urban fire fighting, disaster prevention, disaster assessment and forecasting, urban planning and other public emergency safety management areas, including civil aviation, mining and petrochemical enterprise security management and emergency rescue decision support and other fields, which can provide emergency management of digital technologies and methods to improve the ability and efficiency of emergency management for the urban disaster prevention and relief, responding to public emergencies, mining enterprises safety and protection [7-10]. As one important part of the information technology (IT), GIS has combined with global positioning systems (GPS) and remote sensing (RS), constitute a "3S" integrated system and it has integrated with the Computer Aided Design (CAD) method, communications, internet and virtual reality technology etc, which have combined to form a comprehensive information technology and widely used in public safety management in all areas. Based on the information network technology, the emergency management system and platform applications and construction have begun to take shape, which have played a guiding role in the safety management of petrochemical enterprises and major disaster emergency relief work. But there are still a large number of petrochemical leaks, fires & explosions and other accident disasters occurring frequently and the consequences of loss shocking greatly, which also revealed many problems still in the process of emergency management and rescue of dangerous chemicals [11]. Mainly problems are listed in the following aspects.

1. The emergency response system has not been built according to the HSE modern emergency management framework model, which has not taken the major hazard controlling, accident prevention, harm trend predicting and emergency preparedness, emergency response and disaster recovery as the overall system. Now the emergency response system is still a single disaster management model which pays more attention to disaster relief and neglects fire prevention.

2. The emergency response system is less systematic, complete and relevant, in which the emergency response force planning has not complied with the hazard risk features and accident-scale of the protection zones. The emergency planning is lack of pertinence and practice according to the disaster development.

3. The function of the current emergency response system and information platform for decision-making is too simple that most of the emergency management systems are only focusing on the digital hazard management, hazard identification, hazard evaluation, accident consequences analysis and so on, which have not yet realized the evolution of accident dynamic process and disasters development forecast. It is inadequate to propose appropriate response strategies support aiming at accident scenarios, especially to the disaster signs early warning and disposal.

In order to improve the Petroleum chemical industry fire safety emergency management capabilities and skills, the multi-objective and multi-stage digital integrated emergency management systems with fire hazard prevention and emergency response based on fire risk analysis and forecasting were proposed in the paper, which involved integrated information technology, risk assessment, hazard monitoring, forecast and early warning, dynamic decision-making, comprehensive coordination, emergency response, optimized decision-making and other functions according to the fire & explosion features and the layers of protection to the dangerous of petrochemical enterprises. Using the emergency management platform developed from the emergency management technology system, the petrochemical enterprises can realize dynamic security risk management, thereby enhancing the level of fire safety management and fire prevention technology.

2. Petroleum and chemical fire risk prediction

2.1. Fire hazards and fire mode analysis

According to the products features, petrochemical enterprises can be divided into the oil and gas storage and transportation business, the oil refining companies with the midstream and downstream industry chain, as well as fine chemical companies with petroleum products as raw material. For different types of chemical companies, the characters of
the fire hazard form and distribution are different. Storage Petrochemical enterprises are involved in large number of oil & gas storage and transportation. The main fire hazards in this kind of petrochemical enterprises include: a large amount of flammable explosive oil and gas storage tanks, oil and gas pipelines and transportation. The main fire & explosion accident types are: tank lightning and static fire, tank and pipeline leakage fire, explosion, fire ignited, the impact fire, boiling liquid evaporate vapor explosion (BLEVE), vapor cloud deflagration, physical explosion, explosion of energetic materials and so on, mainly in the form of pool fire, jet fire, and fire flows. While for the oil refining enterprise with industry chain, there is not only a large amount of flammable liquid, superheated liquids and other dangerous chemicals, but also some high temperature and pressure, presence of hydrogen and other complex high-risk chemical production equipments and processes, in which the form of fire & explosion and hazards evolution and spread process are relatively complicated. During the disaster the fire burning fiercely with high radiant heat and it is easy to spread large area of fire that it is possible to cause the device collapse and explosion. While the main hazardous materials in the fine chemical enterprises not only include the oil refinery products, but also other dangerous chemicals materials and technological process, which is possible to burn and explosion, such as material handling, crushing, mixing and distillation, drying technology and equipment, etc. The main casualty devices (including storage tanks and pipelines) leakage fire, explosion, technology and equipment out of control fires, explosions. Typical types of disasters and accidents include explosion, jet fire or pool fire, flowing fire and so on caused by combustible gas or steam leakage from the device.

2.2. CFD-based fire risk analysis and prediction methods

Chemical fire, explosion and accident evolution are not only related to the cause of the fire, device type and size, flammable & explosive chemicals reserves, regional security planning, but also related to its technical equipments, emergency response measures and other related factors. Therefore, for the quantitative and dynamic analysis of petrochemical fire risk, it is important to analyze the fire and explosion accident scenario on the base of hazard identification firstly. Then according to the types of petrochemical enterprises, fire hazards distribution, dangerous process and the device characteristics, the accidents models and evolution rules of leakage, fire & explosion and other disasters can be analyzed.

Fig. 1. CFD-based fire risk analysis and prediction assessment method flow chart.

Based on the devices operation and fire accidents data statistics, the dangerous devices invalidation status and fire accidents forecasting can be analyzed from the dangerous devices routine operation monitoring signals. Using the event tree analysis (ETA) method to construe the possible accident scenarios of the hazard process and devices, using the fault tree analysis (FTA) method to analyze the cause and the causal factors of each accident scenario, according to the patterns of the accident scenario, using the fire & explosion dynamics theory and the evolution models, based on CFD models and fire & explosion dynamics simulation software, such as FDS, FLACS, KFX [12-14] etc, the rules and process of the accident scenario evolution including hazards consequence can be simulated, predicted and analyzed. Combining the effectiveness analysis of the firefighting equipment and emergency response techniques, the fire & explosion accident trends and consequences can be forecasted. For the different accidents scene modes, through the analysis of the fire statistical data, the petrochemicals fires risk effect factors and accidents probabilities can be studied, in combination with probability analysis of fixed fire fighting equipments reliability for the petrochemical facilities, the probability of the petroleum chemical plant fire accidents scenario occurrence and evolution can be estimated and analyzed. Based on the probability analysis of fire hazard
scenarios development trend, consequence and disaster evolution, the quantitative and dynamic fire risk analysis of petrochemical storage area on the different fire scenes can be realized providing technical support and guidance for fire prevention, disaster prediction and fire-fighting system setting. According to the above analysis, petrochemical fire risk analysis and forecast evaluation process based on the CFD technology are shown in Fig. 1. By building the accurate petrochemical enterprises plants process and plant physical model, using CFD simulation models, the whole process of fuel & gas leaks spreading range and oil fire spread including gas cloud explosion and flame propagation caused by accidental ignition can be simulated. Through the simulated calculation, the affected scope and damage extent of the disaster can be analyzed. And the consequences effects, the evolution rule and development trends of chemical industry accidents can be predicted in detail.

3. Petrochemical enterprise emergency management system of fire safety

Emergency management is the process of integrating all aspects related resources to cope and deal with sudden accidents effectively in order to prevent and eliminate the potential fire accidents, reduce accident hazards and optimize decision-making to copy with pre-warning, early disposal and emergency response, based on analyzing of the accidents cause, process and consequences. The emergency management can be divided into five stages generally: crisis detection and early warning, detection and prevention, hazard control, disaster recovery and emergency review. Correspondingly fire safety emergency management mainly include: fire prevention and early warning, fire detection and alarm, fire fighting and rescue, disaster recovery and fire cause investigation and review. In recent years, with rapid development of petrochemical industry in China, large petrochemical plant fire safety level of emergency management has been greatly improved, fire rescue capability has been significantly enhanced, but in aspects of the daily management of fire safety, fire-fighting and rescue capabilities and overall comprehensive coordination capability, management capability of fire safety and fire emergency response system, there are still many problems:

(1) Enterprise fire safety emergency capacity-building is not enough relatively. Petrochemical enterprise fire safety emergency building is still focus on general establishment for the emergency plan, but not for the fire accident scene.

(2) Petrochemical fire emergency warning mechanism is weak. “Emphasize the reaction afterwards, lighting warning of signs.” The accident analysis for the detection and early warning capacity is insufficient to predict the accident.

(3) Petrochemical fire emergency rescue force is backward. Because of the absence of fire safety emergency rescue force standards and specifications, now fire emergency rescue forces in most petrochemical plants are insufficient, technical methods are backward, which is difficult to play its emergency rescue capabilities effectively.

(4) Fire safety emergency management information miscommunication. Communication and sharing within enterprises, between enterprises and fire departments are not enough, hazard source and accident statistics information are not standardized and clear, the lack of comprehensive information on statistical analysis.

3.1. Multi-objective and multi-stage fire emergency management based on fire risk prediction

Considered the whole process of the fire accidents in the petrochemical plant, the usual safety protection measures mainly include four types and stages. Firstly, during the plant planning and design stage, the intrinsic safety protection is the most important safety measures which control the plant process and prevent process accidents and devices deviation. The second is the safety monitoring and supervision measures through which to detect the leakage dangerous materials and potential accidents signals in the dangerous equipment and instrument areas to provide the pre-warning signals and process safety disposal measures. The third is accident disposal technical measures such as firefighting techniques which to control the fire accidents spreading and development till to eliminate the accidents. The fourth is the hazard controlling and safety evacuation measures which to limit the imperiling range of accidents hazard and protect the safety of life. The four stages of safety protection measures just compose four layers of safety protection in the whole plant.

According to the different layers of safety protection measures in the petrochemical plant, the emergency management systems should realize different objectives and responding stages. For the first layer of intrinsic safety protection, the emergency management should focus on the routine safety monitoring and management of the process and equipments. Once the process or equipments occurring failure, the emergency management triggers the second startup program to carry out pre-warning and primary safety disposal. In the third stage of layer protection, the emergency response should focus on the accidents evaluation, emergency resources management and command decision through emergency response platform. Petrochemical enterprises in the event of fire & explosion accidents, it need the police, fire safety supervision departments and other organizations to be unified to carry on the deployment of emergency resources, coordination, linkage to carry out emergency rescue under emergency command mechanism. Due to the complex causes of the petrochemical spills, fires, explosions, failure of devices, process control and process defects such as device technology factors, including human error,
mismanagement and other human factors, there is some chance of probability and sudden characteristics on the occurrence of the accidents. Existing emergency managements are mainly depending on the monitoring to carry on the emergence deployment in accordance with the emergency settings plans, which is often lack of evolution forecasting and early warning on accidents process and development. Moreover the emergence disposal plans are mostly determined by on-site decision to make contingency plans. The fire emergency management is required to analyze risk of the fire hazard and predict the fire hazard evolution based on the fire risk prediction, which can determine the possible disasters mode in the region model, the accident evolution trends, affecting regional and extent of risk, accident probability and other related factors. And according to the risk prediction and analysis results, emergency measures, emergency response resources and equipments, emergency routes and other content related to contingency plans should be set up. Risk prediction based of the emergency management models focus on the different stages and objectives, such as accident prevention, risk prediction, early warning and emergency response decision. And it is important to deploy the prevention and early warning measures before the accident or on the initial stages, by which to carry on the continuous monitoring on the position of the hazard technology process, equipments and operations about the abnormal temperature, pressure, level changes and component concentration parameters on-line monitoring and analysis, in order to achieve early warning of potential risks and disposal, control of the hidden dangers in the bud stage, and avoid disasters and accidents happening.

According to the features of the petrochemical enterprises fire hazards and fire & explosion accidents, based on the chemical emergency response procedures, the pattern of multi-objective and multi-stage fire safety emergency management based on fire risk prediction is shown in Fig. 2.

3.2. Structure of fire safety emergency management system

It can be taken advantage for the emergency rescue capabilities of whole enterprise or regional to improve the efficiency of emergency management, by the establishment of mutual coordination, unity of command, clear responsibilities and specific emergency management system. For different types of petrochemical enterprises, the fire safety objects and focus on the emergency management including the relevant emergence plans and measures are all different in accordance with its own special fire hazards characteristics, but the basic pattern of the emergency response system is almost consistent with the basic constitution. AS shown in Fig. 3, the basic component elements of petrochemical fire safety emergency management system are usually composed by the organization, operation mechanisms, systems and emergency support system four major sections.

Fig. 2. Fire safety emergency management flow chart based on the fire risk prediction.

Fig. 3. Basic component elements of fire safety emergency management system.
In addition to enterprise routine fire emergency management, in the event of fire or explosion, the emergency management system should provide pre-warning and early disposal decisions on the beginning of the accidents. At the same time, the emergency management keeps continuous monitoring and evaluation based on the hazard analysis and prediction. Through the decision analysis and hazard forecasting, the emergency system organizations or agencies will coordinate the operation to carry out emergency response of fire-fighting and rescue action under the effective decision-making support of Fire Safety Emergency Management Command and Control System platform. When the enterprise or regional emergency forces or resources are insufficient to control the hazard development, the emergency system reaches to the higher responding stage and can resort for a higher level emergency response system, or other professional help. Fig. 4 shows the accidents of hazardous chemicals, emergency response system operating structure.

Fig. 4. Petrochemical enterprises or regional fire emergency response system.

3.3. Fire safety emergency management platform

Bring the advanced information technology (GIS, GPS and RS etc.) used in the fire safety emergency management based on the fire-risk prediction, it can realize the accidents’ real-time online monitoring and pre-warning of the petrochemical enterprises processes and devices. Based on the GIS platform, through the hazard identification and statistical analysis of chemical plants or petrochemical area, the MapInfo’s integrated graphics development tools and MapX of C/S models were employed to develop risk source database, monitoring database, graphics library, model base, knowledge base and other information query library. Based on the requirements of accident pre-warning and emergency system development for the large petrochemical plants, in addition to their application of practical work, the major hazard prevention, forecasting and pre-warning decision support system based on risk analysis can be designed and developed which can be used to provide decision support for the petrochemical plants fire safety management and the relevant government departments fire monitoring and emergency rescue. Petrochemical plants risk management system features map is shown in Fig. 5.

Fig. 5. Petrochemical major functions of enterprise risk management system.
(1) Basic information layer

① The database includes production, technical data (including production equipment, and corresponding production process, material properties and quantities, public and fire safety engineering etc.), major hazard data, calculated data and other major hazards.

② Graphics library includes petrochemical area and plants digital map, the plants floor plan (including the surrounding roads, fire department, enterprises, personnel, property and public facilities in case.)

③ Model library includes the value of major hazards model, the accident impact gradient of major hazards model, and the regional loss calculation model of major accident.

④ Knowledge base includes the mechanism and process analysis of major accidents, safety facilities within the affected area of protection, hazard monitoring and control, major accidents and community enterprises and other emergency response plan.

(2) Information processing layer

Through the measurement of the major hazards nature, size, location and contour lines in the region, determine the impact of regional hazards and their distribution, it can provide the evidence of the prevention for the priority hazardous sites and areas. By calculating the affected regional losses extent of the major hazard accident, the status of the major accidents which is possible to effect the entire regional area can be determined to provide the foundation for the preparation of emergency plans. According to the accident mechanism, models, processes, influenced regional and the extent of losses caused by the major hazard, the contingency plans for major accidents can be developed.

(3) System interface layer

MapInfo-based electronic map (including rivers, roads, buildings and other terrain, with a variety of editing, scaling, partial layer changes, the results show graphics and other functions) as a platform, according to user need, display:

① Enterprise basic information;

② Major hazard nature, size, location and contours;

③ Major hazard losses occur on the regional level;

④ Accident simulation prediction

⑤ Major Emergency Plan;

⑥ Fire fighting forces optimization;

⑦ Accidents hazard forecasting;

⑧ Hazard evacuation Simulation and prediction.

4. Conclusions

Through the analysis of the petrochemical industry fire hazards, accident mode and its evolution characteristics, the CFD based technique petrochemical fire risk analysis, prediction and evaluation methods are established. Based on analysis of the emergency management system current status and the layers of accidents hazard prevention measures, the fire safety and emergency management system based on the fire risk forecasting is put forward, which make use of GIS geographic information system platform to take the fire risk prediction, monitoring and control, accident forecast and pre-warning, dynamic decision-making, comprehensive coordination, emergency response, optimized decision-making functions into integration, moreover to establish the emergency response system of prevention and emergency management based on fire risk analysis and prediction.

The emergency management system platform focus on potential accidents in the initial stage of early prevention and pre-warning, which can conduct the risk analysis and fire hazards prediction in the jurisdiction areas. According to the results of the risk analysis and prediction, the emergency measures, emergency response resources and equipments, emergency rescue routes and other related contents of contingency plans can be setup scientifically and pertinently. The emergency management based on risk prediction can realize the dynamics safety management for the petrochemical enterprises fire risk, thereby enhancing the abilities of petrochemical fire safety management and technology levels of fire prevention.

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References