Risk quantitative calculation and ALOHA simulation on the leakage accident of natural gas power plant

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Abstract

In order to study gas leakage accident risk in Natural Gas Power Generation Co., Ltd. and its impact on the surrounding residents, we analysis the accident scenes of natural gas power plant and accident scenes which may occur in the key hazardous areas. By taking the pipeline leakage accident in the last branch lines station as example, the diffusion statuses were simulated by using ALOHA after the natural gas leak. The frequency of pipeline leakage accident and the consequences in the power plant were analyzed. Then individual risk and social risk were obtained. The results show that social risk of the plant is related to the population distribution near natural gas pipelines and the factors of death probability. Assuming three kinds of leak conditions that leakage apertures are respectively 100mm, 200mm and 1200mm, the individual risk and social risk are beyond the acceptable range. When pipeline leakage aperture is 100mm, rescue and evacuation shall be promptly carried out in the power plant and the leakage accident has no effect on the town. When pipeline leakage aperture is 200mm, people should immediately control the leak and make the explosion-proof measures from 55m to 92m of the power plant downwind which is in the range of natural gas explosion limits. When pipeline leakage aperture is 1200mm, emergency evacuation measures should be taken and prevent accidents expanding in most of the town which is in the range of natural gas explosion limits. The results of the quantitative risk calculations and ALOHA simulations provide bases and decisions for the pipelines plan, construction of natural gas power plant and the spatial location of the town.

Keywords: leakage accident in natural gas power plant; ALOHA simulation; risk quantitative calculation; diffusion analysis

1. Introduction

With the development and improvement of West-East Natural Gas Transmission Project and Project of Natural Gas Sent from Sichuan to east in China, the range of applications of nature gas which is a clean, efficient energy and high-quality chemical raw material continues expanding and natural gas power generation becomes an important aspect. Now considerable numbers of the natural gas power plants are located in the densely populated areas of cities whether it is a reformation from coal-fired electricity or a new power plant. The security of natural gas power generation has become an important content of city public safety. According to the survey research, the major accidents are generally due to natural gas leakage which is including pipelines leakage, process equipments leakage and auxiliary facilities leakage in the process of power generation, and then leakage causes fire and explosion. The main component of natural gas is methane, and it contains small amounts of ethane, propane, butane and other alkanes. The explosion limits is low and is 5%-15%. If natural gas leak, it may become...
mixture of explosive gas which is easily mixed with air and cause fire and explosion when met fire source. The result may have an impact on the residents around the Power Plant and social stability. Even it causes a major accident of cluster die and wound. For example, Kaixian had a blowout accident in December 23, 2003. It had killed 243 people and evacuated 100,000 people. Renshou County, Sichuan Province occurred natural gas pipelines explosion in January 20, 2006. It had killed 243 people, and 4 people seriously injured. 30 people slightly injured and 1837 people were evacuated around the scene of explosion. Therefore, it has a great significance of the risk research on leakage accidents for natural gas power generation and the environmental impact of the plant surrounding communities by simulating the diffusion statuses after natural gas leakage. And it provides a theoretical basis for developing the procedures about safe operation and maintenance of natural gas power generation.

The study takes Natural Gas Power Generation Co., Ltd. as an object, and uses the model of accident frequencies and consequences [1-2]. On the basis, procedures about risk analysis are established as natural gas leakage causes jet fire. Through drawing inferences about other cases from one instance, we explore new ideas of security of natural gas power generation which are in the management of urban public security. Personal risk and social risk are studied by drawing the corresponding graph of social risks, and the diffusion statuses are simulated by using ALOHA. It provides technical support for natural gas in power generation safety.

2. Hazard identification and accident scene analysis of natural gas power generation

There are many accident risks which contain fire, explosion, poisoning, suffocation, electric injury, mechanical injury, falls, against objects, burns frostbite, noise and vibration injury in the production process of natural gas power generation [3]. In a variety of risk factors, leakage and diffusion of natural gas are the most important risk factors, and fire, explosion, poisoning and suffocation accidents caused by leakages are the focus of attention and prevention in the production and maintenance process. The study of Natural Gas Power Generation Co., Ltd. is taken as an example, and the layout is shown in Fig 1. The key risk areas and key parts contain the last branch lines station for the natural gas transportation, the regulator station, key valves, technology equipments and pipelines at the plant.

According to the analysis of the accident scene, accident scenarios that occur in the company's key and danger zones are obtained. It is shown in Table 1. Probability of occurrence is given a brief description. Tools and models which are suitable for using for the quantitative assessment of consequences are given. From Table 1, jet flame occurs in the highest frequency caused by the pipeline leakage accidents in the last branch lines station. And limited space explosion is most likely to occur as the regulator and pump with pressure leak in the pressure regulating stations and plants. Heat radiation effect of jet flame which is the most serious cases is analyzed. Further discussion about leakage accident risk of pressure regulating stations and plants can be made by analyzing similarly pipeline leakage.

Fig. 1. Layout of natural gas power generation co., ltd.
Table 1. Accident scene analysis of natural gas power plant

| Accident scenes                      | Possibility of key and danger zones in natural gas power plant | Computational tools |
|--------------------------------------|----------------------------------------------------------------|-------------------|
| Poisoning and suffocation            | The last branch lines station Key valves The regulator station The plant | High High High High Gaussian model |
| Flash fire                           | The last branch lines station Key valves The regulator station The plant | Lower Lower Lower Lower ALOHA |
| Jet fire                             | The last branch lines station Key valves The regulator station The plant | Higher Higher High High ALOHA |
| Vapor cloud explosion                | The last branch lines station Key valves The regulator station The plant | Low Low Low Low ALOHA |
| Limited space explosion              | The last branch lines station Key valves The regulator station The plant | High High Low Higher ALOHA |
| Overpressure explosion               | The last branch lines station Key valves The regulator station The plant | Higher Higher Higher High Brode model |
| Safety diffusion                     | The last branch lines station Key valves The regulator station The plant | lower lower lower lower ALOHA |

3. Determination of accident probability

Accident probability is an important basis for risk management, and how to determine accident probability is a complex process. Many scholars have done many research works in this area, such as Prof SHAO Hui, et al in Changzhou University proposed the method of determining the probability based on the information diffusion [4]. In addition, by using the quantitative calculation of risk, frequency of events is often obtained based on historical accident statistics. Table 2 gives the statistics of gas pipeline accident rate in Europe, and the following calculations will refer to these data.

Assuming that natural gas pipelines leak in the last branch lines station, Leakage aperture may have three forms: small hole \(d_1=100\text{mm}\) middle hole \(d_2=200\text{mm}\) and large hole \(d_3=1200\text{mm}\). To analyze individual risk, accident rates of different types of accidents are needed to determine. As lacking of statistics of the natural gas pipeline, this article refers to the European statistics of gas pipeline accident rate in Table 2 [5]. Table 2 shows that the sum of all types of accident rates is \(5.81\times10^{-4}\text{ km}^{-1}\cdot\text{a}^{-1}\).

Table 2. European natural gas pipeline accident rate statistics

| Types of accidents                  | Accident rate/(km\(^{-1}\cdot\text{a}^{-1}\)) | The proportion in total accidents /% | The proportion of different rupture holes /% |
|-------------------------------------|---------------------------------------------|--------------------------------------|-------------------------------------------|
|                                     |                                             |                                      | Small hole | Middle hole | Large hole |
| External interference               | \(3.00\times10^{-4}\)                      | 51                                   | 25          | 56          | 19         |
| Material defect                     | \(1.10\times10^{-4}\)                      | 19                                   | 69          | 25          | 6          |
| Corrosion                           | \(8.10\times10^{-5}\)                      | 14                                   | 97          | 3           | <1         |
| Surface movement                    | \(3.60\times10^{-5}\)                      | 6                                    | 29          | 31          | 40         |
| Other types                         | \(5.40\times10^{-5}\)                      | 10                                   | 74          | 25          | <1         |
| Total                               | \(5.81\times10^{-4}\)                      | 100                                  | 48          | 39          | 13         |

4. Risk calculation and consequences simulation of natural gas leakage accident based on ALOHA

The spatial location between a Natural Gas Power Generation Co., Ltd. and a town are shown in Fig 2. Population density of the town is 2000 people/km\(^2\). The distance between natural gas pipelines in the last branch lines station and a town is 459m. The diameter of gas pipeline is 1300mm, and the operating pressure of gas pipeline is 10MPa. Personal risk in 50m distance away from gas transmission pipeline and social risk between the plant and the town is analyzed.

4.1. Natural gas pipelines leakage based ALOHA simulation

The relative density of natural gas is 0.58, which is far less than the air. Because the gas in the pipeline has a very high internal pressure, a lot of gas will eject instantaneously when pipelines rupture. Therefore it belongs to air mass diffusion. When natural gas leak into the air and its volume fraction is from 5.3% to 15%, the explosion occurs.

Assuming weather conditions is that east wind is 3m/s, temperature is \(15^\circ\text{C}\), the grade of atmospheric stability is C, and no temperature inversion when the nature gas leak. The diffusion concentrations of natural gas when simulating pipelines leakage
situation are divided into less than 5.3%, 5.3% to 15% and greater than 15%.

Fig. 2. Spatial location of natural gas power plant.

4.1.1. Status of natural gas diffusion when pipeline leakage aperture is 100mm

The simulation result about natural gas diffusion situation when pipeline leakage aperture is 100mm is shown in Fig 3. The simulation result shows that a very small amount of natural gas leaks when pipeline leakage aperture is 100mm, and only the distance is from 27m to 40m in the downwind is in the explosion limits. So the software cannot effectively draw the diffusion situation figure. In fact, because the distance between the plant and a town is 459m, pipeline leakage would not cause a wide range of dangerous incidents and has no impact on the residential areas. Staffs that are close to the leak point should be withdrawn rapidly, and sources of fire which is easy to produce higher ignition energy should be isolated. At the same time, dedicated staffs should be sent to close the pipeline valves. Only in this way can we effectively prevent accidents. However, disoperation will expand the risk of accident. If the explosion is occurred within the area of explosion limits, may lead to damage large areas of gas pipelines and cause the more serious accident.

Fig. 3. Status of natural gas diffusion when pipeline leakage aperture is 100mm.

4.1.2. Status of natural gas diffusion when pipeline leakage aperture is 200mm

The simulation result about natural gas diffusion situation when pipeline leakage aperture is 200mm is shown in Fig 4. The simulation results show that a large amount of natural gas leaks when the pipeline leakage aperture is 200mm, and the distance from 55m to 92m in the downwind is in the explosion limits. People who are in fan-shaped areas of the evacuation figure should be evacuated and set up a cordon. As natural gas has fully spread in dozens of seconds after the pipeline rupture, helping evacuation should be quickly and effectively organized in the area of explosion limits, and the evacuation should be guided for people who are outside the area of explosion limits. At the same time, people should promptly take measures to stop the leakage of natural gas pipelines, and set up the warning signs to prevent fire source.
Fig. 4. Status of natural gas diffusion when pipeline leakage aperture is 200mm.

4.1.3. Status of natural gas diffusion when pipeline leakage aperture is 1200mm

The simulation result about natural gas diffusion situation when pipeline leakage aperture is 1200mm is shown in Fig 5. The simulation results show that a very large amount of natural gas leaks when the pipeline leakage aperture is 1200mm, and the distance is from 382m to 639m in the downwind is in the explosion limits. Natural gas has fully spread within a few minutes after the pipeline ruptures. In this case, the pipeline leakage accident in the power plant has a greater impact on a town. As the distance between the plant and the east part in a town is less than 382m and concentration of natural gas is very high, it easily leads to suffocation in the range. So the staffs should take measures of emergency evacuation in the range of less than 382m. For the residents living outside the east part of a town that the distance is from 382m to 639m, they will not have the risk of suffocation in a short period. It is still easy to cause natural gas explosion by the friction in the process of action because this place is in explosion limits. Therefore, helping evacuation should be timely organized by specialists. The evacuation should be guided for the people who are outside the area of explosion limits and still in the danger zone. The staffs who are outside the danger zone should take measures of free evacuation. As a very large amount of natural gas leaks, it may affect the nearby factories or service areas. To deal with this extreme case and prevent causing significant casualties and property losses, departments and units should develop good evacuation routes in advance and train the specialized personnel who are assisted with evacuating and blocking the hazardous areas.

Fig. 5. Status of natural gas diffusion when pipeline leakage aperture is 1200mm.

4.2. Quantitative calculation of risk

Accident consequences can be calculated from the model of accident consequences. Model of consequences and the accident frequency are integrated to get personal risk and social risk of industrial hazard sources.

Calculation of personal risk for industrial hazard sources is shown in equation (1) [6].
\[ IR = P(1)\sum_{i=1}^{m_1} r_1(i) + P(2)\sum_{i=2}^{m_2} r_2(i) + P(3)\sum_{i=3}^{m_3} r_3(i) + \ldots + P(n)\sum_{i=n}^{m_n} r_n(i) \] (1)

where \( P(n) \) — the probability of industrial facilities of dangerous source corresponds to the number \( n \) potential accidents;

\( P(n)\sum_{i=n}^{m_n} r_n(i) \) — the number \( n \) possible accident scenario corresponds to the possible consequences.

Calculation of social risk for industrial hazard sources is shown in equation (2).

\[ S(N) = \sum P(r_n(i)) \quad \text{Among}(r_n(i)) \geq N \] (2)

Equation (2) expresses the account probabilities of the number of deaths in all accidents which are greater than or equal to \( N \).

### 4.2.1. Analysis of accident consequences

The release rate of gas \( Q \) can use equation (3)[7].

\[ Q = 1.783 \times 10^{-3} \frac{A_p \alpha_i p_o \times \max(0.3, \frac{1}{\sqrt{1 + 4.196 \times 10^{-2} \alpha_i^2 L / d}})}{\sqrt{1 + 4.196 \times 10^{-2} \alpha_i^2 L / d}} \] (3)

where \( A_p \) — Cross-sectional area of pipe, \( m^2 \);

\( \alpha_i \) — Dimensionless pore size (Hole area/ Cross-sectional area of pipe);

\( p_o \) — operating pressure in the gas pipeline, Pa;

\( L \) — Distance between the leakage pipeline and the power plant (assume 50m) m;

\( d \) — Diameter of the pipe, m.

The damage radius of jet flame is shown in equation (4).

\[ r = 10.285 \sqrt{Q} \] (4)

The probability of personal injury caused by the thermal radiation is calculated by equation (5).

\[ Pr = 16.61 + 3.4 \ln \left( \frac{Q}{h^2} \right) \] (5)

where \( h \) = 50m.

The probability of death injury caused by the accident is shown in equation (6).

\[ p = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-0.5 s^2} ds \] (6)

### 4.2.2. Calculation of individual risk and social risk

1. Individual risk

   According to the calculation methods of individual risk for industrial risk sources, the total value of individual risk is 0.377 and it is shown in Table 3. So far, there are no acceptance criteria about pipeline risk, and the criterion of personal risk is adopted by the criteria of UK. The maximum acceptable level of individual risk is \( 10^{-4} \) person/a, and the calculated personal risk is beyond an acceptable level range. So the risk is unacceptable. Table 3 shows that different leakage apertures in a certain range cause different number of deaths. When the leakage aperture is larger than a certain value, it will lead all the residents to die in a town.

2. Social risk

   According to the calculation methods of social risk for industrial risk sources, the relationship between different number of deaths and the cumulative rate of accidents is obtained. Social risk curve is drawn, and it is shown in the Fig 6. Number of deaths and the cumulative rate of accidents can be calculated by the following equations [7].

Number of deaths:

\[ N = \int_0^{A_i} \rho_s P dA_i \] (7)

where \( A_i \) — the radius in the harm region \( A/\text{km}^2 \);
\( \rho_p \) — the population density \( \text{km}^{-2} \);
\( p_i \) — probability of death for all types of accidents.

The cumulative rate of accidents:

\[
F = \sum_{i=0}^{L} \varphi u(N_i \geq N)
\]

(8)

where \( u(N_i \geq N) \) — unit function (If \( N_i \geq N \), then \( u = 1 \); if \( N_i \leq N \), then \( u = 0 \));
\( L \) — the length of the pipeline in the danger zone;
\( \varphi_i \) — different accidents lead to the accident rate.

As there is not a standard system of social risk evaluation in China, the acceptable level of social risk in British is adopted\([8-9]\). It is shown in Fig 6. By comparison, social risk has exceeded to the acceptable range, and social risk is unacceptable.

| Leakage aperture of pipeline | \( d_1 \) | \( d_2 \) | \( d_3 \) |
|-----------------------------|--------|--------|--------|
| The rate of gas release     | 139.82 | 557.90 | 19066.66 |
| Injury radius \( r/m \)     | 121.61 | 242.93 | 1420.17  |
| The areas in the harm region \( A/km^2 \) | 0.0464 | 0.1853 | 6.3330   |
| The length of pipeline in the danger zone \( L/m \) | 221.7  | 475.44 | 2838.56  |
| The probability of personal injury caused by the thermal radiation | 6.81   | 11.51  | 23.517   |
| The probability of death injury caused by the thermal radiation | 0.964852 | 1      | 1       |
| Number of deaths \( Ni \)/person | 90    | 371    | 12666   |
| Individual risk             | 0.059  | 0.106  | 0.212   |
| Individual risk in total    | 0.377  |        |         |
| The cumulative rate of accidents \( F \) | 0.061  | 0.050  | 0       |

Fig. 6. Social risk curve.

5. Conclusions

(1) As heat radiation effect of jet flame is the most serious consequences, the pipeline leakage accident risk of Natural Gas Power Generation Co., Ltd. is analyzed by the method of quantitative calculation of risk. The results show that assuming three
kinds of leak conditions that leakage apertures are respectively 100mm, 200mm and 1200mm, the individual risk and social risk are beyond the acceptable range. The number of deaths increases with increasing of leak aperture, the cumulative accident rate decreases as the number of deaths increases.

(2) The diffusion statuses are simulated by using ALOHA after the natural gas leak, and distribution of the danger zone under various circumstances is obtained. Recommendations of the emergency measures are put forward.

(3) The results of the quantitative risk calculations and ALOHA simulations provide bases and decisions for the pipelines plan and construction of Natural Gas Power Generation Co., Ltd. and the town.

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