

## Fire Risk Study of Long-distance Oil and Gas Pipeline Based on QRA

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### Abstract

Along with the development of urban construction and industry requirement, more and more long-distance oil and gas pipelines have built and served in China. The leakage of the oil and gas would be happened because of some inner or outer factors during the transportation. If the concentration of the mixture gas composed by oil/gas and air reaches the burning and/or explosion limit, the fire and/or explosion accident resulting in casualties and serious loss of property may be happened once there is a fire source in the surroundings. Therefore, the relevant research on the risk analysis and evaluation to the oil and gas pipeline has been focused on the field of safety engineering in recent years. So it is necessary to carry out the evaluation on the fire risk study to ensure the safety of long-distance oil and gas pipeline. In this paper, the character of the risk of long distance oil and gas pipeline was analysed firstly, and then the fire risk of the long-distance oil and gas pipeline was processed based on Quantitative Risk Analysis (QRA). Taking a natural gas pipeline as an example, the influence area (death radius) and individual risk contour line of fire were charted based on the software CASSTQRA. For the natural gas pipeline, the death radius was 148.42m, and the areas circled by the individual risk contour line of  $3 \times 10^{-7}$  and  $1 \times 10^{-6}$  were not high density residential areas, public gathering places of high density or high sensitive areas, important targets and special high density places. The fire risk of the natural gas pipeline was acceptable. Finally, the corresponding preventing and controlling suggestions to guarantee the safety of the transportation have been proposed in this paper. The results of the study are practically significant to the risk assessment and safety management of the long distance oil and gas pipeline.

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### Nomenclature

$D_0$	split diameter (m)
$\rho_0$	density of leakage gas ( $\text{kg}/\text{m}^3$ )
$\rho$	density of environmental gas ( $\text{kg}/\text{m}^3$ )
$C(x)$	gas concentration ( $\text{kg}/\text{m}^3$ )
$b_2$	distribution parameters
$y$	distance from the selected point to the jet flow axis (m)
$Q_0$	leakage gas velocity ( $\text{kg}/\text{s}$ )
$C_d$	leakage coefficient
$Q$	radiation flux of point heat source (W)
$\eta$	efficiency factor
$H_c$	gas combustion heat ( $\text{J}/\text{kg}$ )
$L$	flame length (m)

### 1. Introduction

As a kind of clear, efficient and high quality known energy, oil and gas have been widely used in the chemical industry, electric power, city fuels, and other industrial and civil fields. With the development of urban construction and industry, more and more oil and gas has been transported by pipelines, and it will be widely used in the future in China. Long-

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distance pipeline has become one of the safest and effective ways for the transportation of oil, gas and other chemicals. But the leakage of oil and gas pipeline would be happened during the transportation, because the gas pipelines may be ruptured by the inner or outer factors such as the corrosion, material ageing, and poor quality and so on. If the concentration of the mixture gas composed by natural gas and air reaches the burning and/or explosion limit, it will possibly deal to the fire and/or explosion accident. According to statistics, many oil and gas pipeline accidents since 2000 in China [1, 2]. Once the fire and/or explosion accidents are happened, the people' lives and the surrounding equipments and buildings would be affected seriously. For examples in China, an underground natural gas pipeline was ruptured, and then the mixture gas exploded on January 1, 2002. As the consequence of the accident, at least six persons were killed; two persons were badly injured and two persons were slightly injuries in Daqing city. Another gas pipeline exploded during the maintenance of the pipelines on April 20, 2004, there were two persons were killed, one person was badly injured and six persons were slightly injuries in the accident in Huainan city. Also, it is well known that there were 62 persons were killed and 136 persons were injured on November 22, 2013 in the oil pipeline explosion accident in Qingdao city. So the risk research on the natural gas transported by pipelines has important practical significance to prevent the personnel security and property safety.

Therefore, it is significant to study the risk of the long-distance oil and gas pipeline to avoid the loss of life and wealth. The relevant research on the risk analysis and evaluation to oil and gas pipeline has been focused in the field of safety engineering in recent years. Some calculation models such as QRA model, UDM model, BM model and FEM3 model have been put forward to simulate oil and gas leakage diffusion and evaluate the risk of the gas pipeline [3-5], and some model were applied in different cases such as chemical equipment, process pipelines and so on [6-8]. Also some software such as the PHAST [9] was used to analysis the diffusion of the natural gas when the leakage happened. But the individual risk of fire accident is important to the risk management of the oil and gas pipeline. So based on the risk analysis of the oil and gas pipeline, fire mathematical model, the jet fire model for oil and gas was built firstly in the paper; the consequence evaluation on the fire accident for oil and gas pipeline was processed based on QRA, the influenced areas and individual risk re charted by applying the software CSAATQRA. Also, some suggestions are brought forward at last in this paper. The results are helpful to the risk evaluation and safety management of the oil and gas pipeline.

## 2. Risk Analysis of Long-distance Oil and Gas Pipeline

### 2.1 Influence Area Analysis

The influence area of long-distance pipeline accidents is an important factor to determine the risk of long-distance oil and gas pipeline. Usually, the affected area can be divided into death radius and injury radius. The influence radius is the threshold distance of the oil and gas pipeline leakage accident, which may not want to be happened with consequences of death, environmental pollution or property loss, etc. Therefore, the influence area of long-distance pipeline is a certain threshold distance from the surrounding.

Because the long oil pipeline accidents may occur in any position in the pipeline, it can be considered as a series of dangerous sources. When the accident of pipeline all hazard point the same scene, on both sides of the pipeline of the influence area can be taken as a circle as the center of accident point, the influenced radius  $R$  is the radius of the circle to move along the pipeline route that can be approximated with rectangular area along the pipeline or circular region [2]. Therefore, the closer to the pipeline, the risk of the impact of the accident is high. The accident consequence of oil and gas pipeline was shown in Fig. 1.

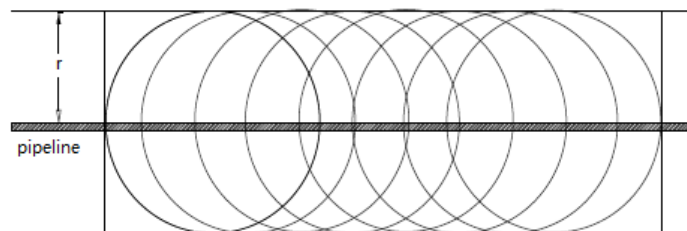


Fig. 1 Chart of influence area of long-distance oil and gas pipeline accident

### 2.2 Individual Risk

Individual risk is the key quantitative index to measure potential life loss and quantitative risk assessment. The so-called individual risk refers to the risk of a variety of potential fire, explosion, and toxic gas leakage accident caused by a fixed position in the region of a fixed position of the individual probability of death, which is the individual mortality. It is usually shown as a risk contour line (as shown in Figure 2), which can measure the size of an individual risk by comparing with an acceptable risk criteria.

In viewing of the risk to the surrounding people, facilities and environment, the acceptable individual risk criterion of the long-distance oil and gas pipeline is defined as other major hazard in China. The acceptable individual risk cannot exceed  $1 \times 10^{-6}$ /year in the high density residential areas (such as residential areas, hotels, resorts, etc.) and public gathering places of high density (such as office, shopping malls, restaurants, entertainment, etc.). The acceptable individual risk cannot exceed  $3 \times 10^{-7}$ /year in the high sensitive areas (such as schools, hospitals, kindergartens, nursing homes, etc.), important targets (such as party and government organs, military management area, cultural relic protection units, etc.) and special high density places (such as large stadiums, large transportation hubs, etc.).

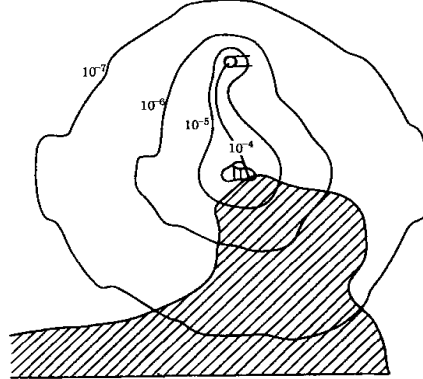


Fig.2 Sketch map of individual risk contour line

### 3. Fire Consequence Mathematical Model

Usually, the fire consequence of the gas pipeline is serious than the oil pipeline. So the gas fire consequence mathematical model is discussed as following.

It is well recognized that the more challenging accident of gas pipeline is a jet-fire, wherever pressurized, or pressure liquefied flammable materials are handled. In particular, a reactive chemical fuelled jet-fire may be more severe than a hydrocarbon pool fire [10-12]. The leaked natural gas with high pressure will be jetted out as a jet flow from the split of the pipeline, if the leaked gas is lit at the split, then the jet fire is happened, the peripheral personnel and buildings would be damaged.

The leaked combustible material with high pressure can form a jet flow, if the gas is lit at the leakage split, then the jet fire is happened. The jet fire model is built as the following [13-18]. The equivalent jet diameter is applied to calculate the jet fire diameter. The equivalent jet diameter can be obtained from the Equation (1).

$$D_{eq} = D_0 \sqrt{\frac{\rho_0}{\rho}} \quad (1)$$

If the density of the leakage gas  $\rho_0$  is equivalent with the density of the environmental gas  $\rho$  instantly at the moment of the leakage, then the equivalent jet diameter  $D_{eq}$  is equal to the diameter of the actual split  $D_0$ . The gas concentration  $C(x)$  where it is  $x$  meters away from the jet origin on the jet flow axis can be derived from Equation (2).

$$C(x) = \frac{\frac{b_1 + b_2}{b_1}}{0.32 \frac{x}{D_{eq}} \cdot \frac{\rho}{\sqrt{\rho_0}} + 1 - \rho} \quad (2)$$

In the above formula  $b_1$  and  $b_2$  is the distribution parameters. The gas concentration  $C(x,y)$  in any point of the perpendicular plane to the jet axis where it is  $x$  meters away from the jet origin on the jet flow axis can be calculated through the Equation (3).

$$C(x, y) = C(x)e^{-b_2 \left(\frac{y}{x}\right)^2} \quad (3)$$

Where,  $C(x)$  is the gas concentration where it is  $x$  meters away from the jet origin on the jet flow axis.

With the increase of the distance to the jet origin, the gas velocity will become lower until it is equal to the wind velocity surrounding when the gas movement will no longer meets the jet flow rule. Therefore, the critical velocity and the critical concentration for the liquid gas should be calculated when the jet fire consequence evaluation is processing.

Suppose that the leakage gas velocity where it is  $x$  meters away from to the jet origin on the jet flow axis is  $U(x)$ , see the Equation (4).

$$\frac{U(x)}{U_0} = \frac{\rho_0}{\rho} \cdot \frac{b_1}{4} \left[ 0.32 \frac{x}{D_{eq}} \cdot \frac{\rho}{\rho_0} + 1 - \rho \right] \cdot \left( \frac{D_{eq}}{x} \right)^2 \quad (4)$$

Where  $U_0$  is the initial velocity of the jet flow,  $U_0$  is equal to the leakage gas velocity when the gas flows across the split.  $U_0$  can be calculated by using the next Equation (5).

$$U_0 = \frac{Q_0}{C_d \rho \pi \left( \frac{D_0}{2} \right)^2} \quad (5)$$

In the calculation of the jet fire heat flux, regard it as a series of point heat source located on the jet flow axis, and the total thermal radiation flux can be calculated by using the jet diffusion Equation.

The thermal radiation flux of each point in the heat source is shown as the Equation (6).

$$q = \eta Q_0 H_c \quad (6)$$

The flame length for jet fire is equal to the distance from the leakage split to the lower limit combustion of the combustible mixture on the jet flow axis. Sometimes in order to simple calculation, the jet flow axis length will be taken as the flame length for jet fire. The flame length for jet fire can be obtained according to the simplified Equation (7). Where the parameter  $L$  stands for the flame length, its unit is  $m$ .

$$L = \frac{(H_c Q_0)^{0.444}}{161.66} \quad (7)$$

The thermal radiation strength  $I_i$  means the radiation strength from some point heat source  $i$  to the location where it is  $x$  meters away from the point on jet flow axis can be obtained according to the Equation (8). The parameter  $\alpha$  stands for the radiation rate, its value is 0.2.

$$I_i = \frac{\alpha q}{4\pi x^2} \quad (8)$$

And then the thermal radiation intensity at  $x$  location is the sum of all the thermal radiation strength from each point heat source to that point.

$$I = \sum_n I_i \quad (9)$$

In the Equation (9)  $n$  is the selected number of the point heat source, generally it is taken as 5.

Accordingly, the potential influence area to person under different harm or damage criteria can be derived from the above Equations.

#### 4. A Case Study

Based on the above fire mathematical model, the consequence chart and individual risk contour line of fire accident after the leakage of the natural gas transported by pipeline can be obtained.

In this paper, a natural gas pipeline was taken as a case to study the fire risk of the oil and gas pipeline. The diameter of the natural gas pipeline was 600mm; pressure in the pipeline was 10 MPa, the length of the pipeline was 5 km. Suppose that a sudden complete rupture was happened and a fire accident was happened during the operating because of the pipe rupture for some reasons.

Based on the results of the influence area analysis and individual risk study, the consequence evaluation on the fire accident for the natural gas pipeline was processed based on QRA, the influenced areas and individual risk contour line will be charted by applying the software CSAATQRA. Inputting all the parameters of the pipeline to the calculating interface, we can get the influence area and individual risk.

The influence area of the fire accident to the person was shown in the Fig.3. The red line area was the person influence area, and the death radius was 148.42m.

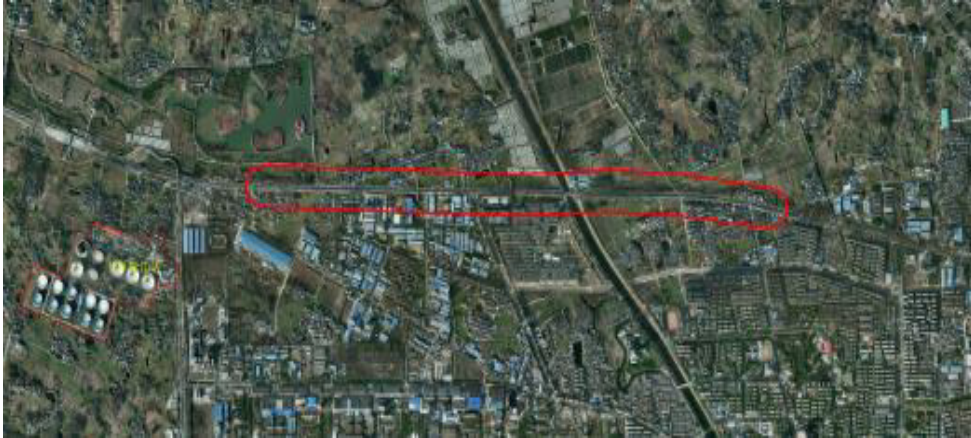


Fig.3 Consequence simulation of jet fire for natural gas pipeline

And then, the individual risk contour lines were drawn in the Fig.4. The yellow line is the individual risk contour line of  $3 \times 10^{-7}$  and the orange line is the individual risk contour line of  $1 \times 10^{-6}$ . It can be seen from the Fig.4, the area circled by the two individual risk contour lines were not high density residential areas, public gathering places of high density or high sensitive areas, important targets and special high density places. So, the fire risk of the natural gas pipeline was acceptable.



Fig.4 Individual risk contour line of natural gas pipeline fire accident

## 5. Conclusions and Suggestions

Through the above research, the following conclusion can be obtained in this paper.

(1) Fire would be happened once the leaked oil and gas mixture with the air is ignited by the igniting source during the transportation in the long-distance oil and gas pipeline. Among three kinds of the fire accident, the more challenging accident is a jet-fire, wherever pressurized, or pressure liquefied flammable materials are handled. The fire risk research on the long-distance oil and gas pipeline has important theoretical and practical significance to promise the personnel and property safety.

(2) The influence area of long-distance pipeline accidents is an important factor to determine the risk of long-distance oil and gas pipeline. The influence radius can be divided into death radius and injury radius. Therefore, the influence area of long-distance pipeline is a certain threshold distance from the surrounding.

(3) The acceptable individual risk criterion of the long-distance oil and gas pipeline is defined as major hazard in China. It cannot exceed  $1 \times 10^{-6}$ /year in the high density residential areas and public gathering places of high density. The acceptable individual risk cannot exceed  $3 \times 10^{-7}$ /year in the high sensitive areas, important targets and special high density places.

(4) The software CASSTQRA is an effective tool to simulate the influence area and depict the individual risk contour line for long-distance oil and gas pipeline. Based on the fire mathematical model and the software CASSTQRA, a natural gas pipeline was taken as an example to calculate the influence area (death radius) and individual risk. For the natural gas pipeline, the death radius was 148.42m, and the areas circled by the individual risk contour line of  $3 \times 10^{-7}$  and  $1 \times 10^{-6}$  were not high density residential areas, public gathering places of high density or high sensitive areas, important targets and special high density places. The fire risk of the natural gas pipeline was acceptable.

(5) In order to prevent the fire, the pipeline enterprise should enhance the daily monitoring, safety management and emergency preparatory, strengthen the daily maintenance and repair in order to prevent the accidents. The main efforts should be done by the enterprise including controlling the fire source, strictly implementing the rules of hot work; strictly implementing the fire regulations, enhancing the fire infrastructure investment; strengthening the safety publicity and education on fire, elevating the safety awareness of the masses; establishing the fire emergency plans and implementing the regular exercise and revision of the emergency plans.

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## References

- [1] Zongzhi Wu, Rujun Wang, 2014. Concern with the safety management of oil and gas pipelines--Status. Chinese Safety News 6, p. 1.
- [2] Wu Zongzhi, Zhang Shengzhu, Yu Lijin, 2014. A method for long-distance oil and gas transmission pipeline route selection based on loss of life. China Safety Science Journal 24, p. 71.
- [3] Young, Do Jo, Bum, Jong Ahn, 2005. A method of quantitative risk assessment for transmission pipeline carrying natural gas, Journal of Hazardous Materials 123, p. 1.
- [4] Han, Z.Y, Weng, W. G, 2011. Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network, Journal of Hazardous Materials 18, p. 509.
- [5] Ma, Lei, Li, Yongshu, 2010. Research and Realization of Urban Natural Gas Pipeline Network Pre-warning System, China Safety Science Journal 20, p.171.
- [6] Zhaoqin Wang, Wenxing Feng, Wu-yi Cheng, 2009. Analysis of Geometry and Hazardous Radius of Jet Flame from High-pressure Natural Gas Pipeline, Safety and Environmental Engineering 16, p. 109.
- [7] Majid, ZA., Mohsin, R., 2012. Failure Investigation of Natural Gas Pipeline, Arabian journal for Science and Engineering 37, p.1083.
- [8] Jianguo Ren, Shunqing Lu, 2006. Application of Gas Diffusion Mathematical Model to Safety Assessment, China Safety Science Journal 16, p. 12.
- [9] Boling Zhu, Xiaochun Yu, 2009. Research for PHAST in the process of liquefied natural gas discharge and dispersion, Computers and Applied Chemistry 26, p.1418.
- [10] Roberts, T., Buckland, I., Beckett, H., 2001. Consequences of jet-fire interaction with vessels containing pressurized, reactive chemicals, Hazardous: Analyzing the past, planning the future 148, p. 147.
- [11] Baozhi Chen, 2011. System safety assessment and forecast (the second edition), Metallurgical Industry Press, Beijing.
- [12] Deming Yu, 2000. Quantitative risk assessment to the storage and transportation process of the inflammable, explosive and toxic dangerous goods, China Railway Press, Beijing.
- [13] Gomez-Mares, M., Munoz, M., Casal, J., 2009. Axial temperature distribution in vertical jet fires, Journal of Hazardous Materials 172, p. 54.
- [14] Cumber, PS, 2009. Efficient calculation of the radiation heat flux surrounding a jet fire, Fire Safety Journal 44, p. 580
- [15] Palacios, A., Munoz, M., Casal, J., 2009. Jet Fires: An Experimental Study of the Main Geometrical Features of the Flame in Subsonic and Sonic Regimes, AIChE Journal 55, p.256.
- [16] Gomez-Mares, M., Zarate, L., Casal, J., 2008. Jet fires and the domino effect, Fire Safety Journal 43, p. 583
- [17] Lowesmith, B. J., Hankinson, G., Acton, M. R., 2007. An overview of the nature of hydrocarbon jet fire hazards in the oil and gas industry and a simplified approach to assessing the hazards, Process Safety and Environmental Protection 85, p. 207.

- [18] Anjuman Shahriar, Rehan Sadiq , Solomon Tesfamariam, 2012. Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis, *Journal of Loss Prevention in the Process Industries*, 25, p. 505.