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Jet Fire Consequence Evaluation on the Natural Gas Transported by Pipelines

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Abstract

Along with the development of urban construction and industry requirement, more and more natural gas has been transported by pipelines. During the transportation, the leakage of the natural gas would be happened because the gas pipelines may be ruptured by the inner or outer factors. 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 resulting in casualties and serious loss of property once there is a fire source in the surroundings. Therefore，the relevant research on the risk analysis and evaluation to the pipeline carrying the natural gas has been focused in the field of safety engineering in recent years. It is well recognized that the more challenging accident is a jet-fire, wherever pressurized, or pressure liquefied flammable materials are handled, so it is necessary to carry out the evaluation on the jet fire and its preventing and controlling measures. In this paper, the model of the jet fire is built firstly, and then the jet fire consequence evaluation on the natural gas pipelines is processed, and aided by the computer-assisted program MATLAB, the relevant datum have been processed and the influenced areas to person and equipment have been charted; 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 natural gas pipeline.

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Keywords:natural gas; jet fire; pipeline; risk evaluation

1. Introduction

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

If the fire and/or explosion accidents are happened for the natural gas transported by pipeline, 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. So the risk research on the natural gas transported by pipelines has important practical significance to prevent the personnel security and property safety.

Therefore，the relevant research on the risk analysis and evaluation to the natural gas transported by pipelines has been

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focused in the field of safety engineering in recent years. Some calculation models such as UDM model [4], BM model [5] and FEM3 model [6] have been put forward to simulate gas leakage diffusion and evaluate the risk of the gas pipeline, and some model were applied in different cases such as chemical equipment, process pipelines and so on. Also some software such as the PHAST [7] was used to analysis the diffusion of the natural gas when the leakage happened. It is well recognized that the more challenging accident 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 [8]. 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. In view of that, the jet fire model for the natural gas is built firstly in the paper; the consequence evaluation on the jet fire accident for the natural gas pipelines is processed, the calculating data and the influenced areas to person and equipment are charted by applying the software MATLAB. Also, some suggestions are brought forward at last in this paper. The results are helpful to the risk evaluation and safety management of the natural gas pipeline.

2. Jet Fire Model

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 [9-16].

The equivalent jet diameter is applied to calculate the jet fire diameter. The equivalent jet diameter can be obtained from the formula 1.

$$D_{eq} = D_0\sqrt{\frac{\rho_0}{\rho}} \tag{1}$$

Where,

D_0: Split diameter, *m*;

ρ_0: Density of leakage gas, kg/m^3;

ρ: Density of environmental gas, kg/m^3

If the density of the leakage gas ρ_0 is equivalent with the density of the environmental gas ρ 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 formula 2.

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

In the above formula b_1 and b_2 is the distribution parameters. The two parameters can be obtained by the following formula 3.

$$\begin{cases} b_1 = 50.5+48.2\rho-9.95\rho^2 \\ b_2 = 23.0+41.0\rho \end{cases} \tag{3}$$

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 formula 4.

$$C(x,y) = C(x)e^{-b_2(\frac{y}{x})^2} \tag{4}$$

Where,

$C(x)$: Gas concentration where it is x meters away from the jet origin on the jet flow axis, kg/m^3;

b2: Distribution parameters;

y: Distance from the selected point to the jet flow axis, *m*.

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 formula 5.

$$\frac{U(x)}{U_0} = \frac{\rho_0}{\rho} \cdot \frac{b_1}{4}[0.32\frac{x}{D_{eq}} \cdot \frac{\rho}{\rho_0} + 1 - \rho] \cdot (\frac{D_{eq}}{x})^2 \quad (5)$$

Where U_0 stands for 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 formula 6.

$$U_0 = \frac{Q_0}{C_d \rho \pi (\frac{D_0}{2})^2} \quad (6)$$

Where,

Q_0: Leakage gas velocity, kg/s;

C_d: Leakage coefficient

When P_0/P is less than *(2/(k+1))(k/(k-1))*, the gas flow is sonic , the leakage gas velocity can be derived from the formula 7. Where P stands for the medium pressure in the container, P_0 stands for the environmental pressure, their units are P_a, and the parameter k stands for the gas adiabatic exponent.

$$Q_0 = YC_d A\rho \sqrt{Rk\left(\frac{2}{k+1}\right)T\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}} \quad (7)$$

Where，

C_d: Leakage gas coefficient, selected between *0.61* and *1.0*;

A: Split size, m^2;

R: Gas constant, *J/(mol.k)*;

T: Gas temperature, K;

Y: Gas expansion factor, for sonic flow, Y is taken as *1*; for subsonic flow, the gas expansion factor can be derived from the following formula.

$$Y = \sqrt{(\frac{1}{k-1})(\frac{k+1}{2})^{\frac{k+1}{k-1}}(\frac{P}{P_0})^{\frac{2}{k}}[1-(\frac{P_0}{P})^{\frac{k-1}{k}}]} \quad (8)$$

When P_0/P is more than*(2/(k+1))(k/(k-1))*，the gas flow is subsonic, the leakage gas velocity can be derived from the formula 9.

$$Q_0 = YC_d A\sqrt{P\rho k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \quad (9)$$

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 formula.

The thermal radiation flux of each point in the heat source is shown as the formula 10.

$$q = \eta Q_0 H_c \quad (10)$$

Where,

q: Radiation flux of point heat source, W;

η: Efficiency factor;

H_c: Gas combustion heat, *J/kg*;

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 formula 2.11. Where the parameter L stands for the flame length, its unit is m.

$$L = \frac{(H_C Q_0)^{0.444}}{161.66} \quad (11)$$

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 formula 12. The parameter α stands for the radiation rate, its value is *0.2*.

$$I_i = \frac{\alpha q}{4\pi x^2} \quad (12)$$

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.

$$I = \sum_{n} I_i \qquad (13)$$

In the formula 13 n is the selected number of the point heat source, generally it is taken as *5*.

Accordingly, the potential influenced area to person and equipment under different harm or damage criteria can be derived from the above formulas.

3. Consequence Simulation Aided by MATLAB

Because the calculation process is relatively complex, therefore the jet fire consequence needs to be calculated by the computer-assisted program.

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. MATLAB can be used to analyze data, develop algorithms, and create models and applications. The language, tools, and built-in math functions can be used to explore multiple approaches and reach a solution faster than the traditional programming languages. So, the computer-assisted software MATLAB is applied to complete the calculation and simulation of the jet fire consequence for the natural gas pipeline in this paper.

Based on the above jet fire combustion model, the consequence and damage of the jet fire after the leakage of the natural gas transported by pipeline can be obtained. Suppose that some jet fire is happened during the operating because of the rupture for some reasons. The split is approximate a circular hole on the pipeline, its diameter is *0.025* m, pressure in the pipeline is $3\ MP_a$, molar mass of the natural gas in the pipeline is *0.0195 kg/mol*, then according to the calculation, it is known that the leakage gas velocity is *2.78kg/S*.

Before the evaluation of the jet fire consequence for the natural gas transported by pipelines, the harm and damage criteria must be determined. In this paper, the harm criteria to person are listed in the table 1, the damage criteria to equipment are listed in the table 2.

Table 1. Harm criteria of jet fire to person

No.	Heat flux (kW/m^2)	Harm effect on person
1	6.5	Death
2	4.3	Serious injury
3	1.9	Minor injury

Table 2. Damage criteria of jet fire to equipment

No.	Heat flux (kW/m^2)	Damage effect on equipment
1	100	Totally destroyed
2	35	Seriously damaged
3	25	Structure components deformed

In the calculation, the jet fire flame direction is taken as the x axis. According to the harm criteria to person (see the table 1) and the damage criteria to equipment (see the table 2), the influenced area under respective thermal radiation intensity can be obtained by running the MATLAB program in the paper. The consequences simulation of jet fire for natural gas pipeline is shown as the chart 1.

The different influenced areas under different conditions are shown with three kinds of colours (as the chart shown). The colour is darker; the more serious is the consequence. For example, in the influenced area of harm to person chart the death area is shown as the red area, the serious injury area is shown as the purple area, and the minor injury area is shown as the yellow area.

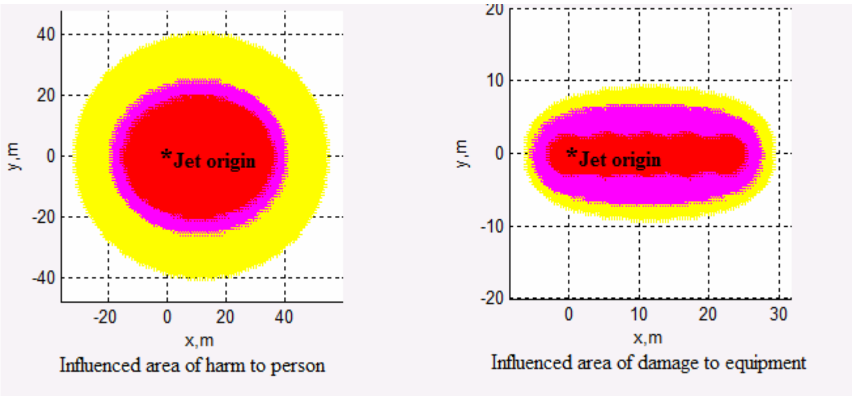

Chart 1. Consequence simulation of jet fire for natural gas pipeline

4. Results

In this example the maximum flame length for jet fire is about 14.16*m* in the consequence calculation. The influenced area of harm to person from the jet fire is listed in the table 3 and the influenced area of damage to equipment from the jet fire is shown in the table 4. So as a result the influenced area of harm to person is from 51.25*m* to 85.08*m*, the influenced area of damage to person is from 27.29*m* to 34.34*m*. Therefore it is suggested that the influenced areas should be taken as the vital zones of the safety management for the enterprise.

Table 3. Influenced area of harm to person from jet fire

Harm effect on person	Distance to Jet origin on *X* axis/*m*
Death	-14.09 to 37.16
Serious injury	-18.32 to 41.39
Minor injury	-31.01 to 54.07

Table 4. Influenced area of damage to equipment from jet fire

Damage effect on equipment	Distance to Jet origin on *X* axis/*m*
Totally destroyed	-2.11 to 25.18
Seriously damaged	-4.93 to 28.00
Structure components deformed	-5.64 to 28.70

It is obvious that the consequences of the jet fire for the natural gas pipeline are so severe that will probably lead to the casualty and wealth loss, so detailed prevention and management should be well done in the daily operation as far as possible to avoid the jet fire accidents.

5. Conclusions and Suggestions

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

(1) 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 risk research on the natural gas transported by pipelines has important practical significance to prevent the personnel security and property safety.

(2) The computer-assisted program MATLAB can be used as one of the effective tool to assess the risk and evaluate the consequence for the natural gas pipeline. Based on the jet fire model, using the aided program MATLAB to carry on data

processing and consequence charting can describe the influenced area of harm to person and damage to equipment when some jet fire accident is happened for the natural gas transported by pipelines.

(3) In order to prevent the jet fire, the 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.

(3) In order to control the consequence of the jet fire, the enterprise should rapidly organize peripheral personnel to leave the dangerous area at the same time immediately take emergency measures to eliminate accident as soon as possible when the accident is happened. The main emergency measures include shutting down the ignition source and cutting off the import of materials; dividing the danger zone at the scene of the accident and implementing the access control; timely plugging and diluting the hazardous materials and so on. In one word, the enterprise should do the best to manage and extinguish all the hazards to avoid the emergency and less the consequences of the accidents.

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