Simulation Study on Influence of Natural Gas Pipeline Pressure on Jet Fire

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Abstract. In order to study the influences of natural gas pipeline pressure on jet fire with FDS (fire dynamics simulation) software, based on principle of fluid mechanics and Thornton flame model, characteristics and hazard scope of the jet fire were comparatively studied for different pipe pressure. The results show that characteristics and hazard scope of the jet fire are largely affected by different pressure. When the pipe pressure is 0.2MPa and 0.4MPa, the size of both leak holes are same, during a same period, the latter flow is greater than the former. When the pipe pressure is greater than 0.8MPa, the leakage hole size is 100mm, and the maximum temperature, diameter and the high temperature affected area of the flame are increased.

1. Introduction
Pipeline transportation is widely used in oil and gas conveying system with the advantages of high efficiency and strong continuity, but there are many hidden dangers. When the pipeline failure, the leaked inflammable and explosive gas can easily cause fire and explosion accidents[1], including jet fire, fireball fire, and vapor cloud explosion. The jet flame refers to a fire that is formed at the leak hole when the gas is leaking[2].

Researchers have conducted the research of natural gas fires for many years, and some developed countries have already developed the theoretical model of natural gas fire and the experimental study of natural gas jet fire[3]. For example, Lowesmith and Hankinson have conducted large scale jet fire experiments on different methane concentrations in natural gas pipelines[4]. Based on the theory of Becker, Kalghatgi did small-scale jet fire experiments in wind tunnels, and studied the influence of different injection angles and wind speed on the characteristics of the jet fire[5].Based on the Kalghatgi jet fire experimental data and Shell Research mathematical model, Chamberlain developed the formula of geometric characteristics of jet fire [6]. In addition, some foreign researchers have analyzed the hazards of natural gas injection, such as Tom Bajcar, who has established a risk assessment system for natural gas metering stations[7]. Zhao established the calculation model of injection fire, analyzed the distribution rule of thermal radiation, and compared the numerical simulation results with the experimental results[8].

Much research has been done to improve the model derived from previous studies, mainly about
the characteristics and the harm of jet fire. For example, Wang studied the possibility of fireball combustion and vapor cloud explosion after a gas leak in an open space pipeline[9]. Wang and Yang analyzed the damage radius of the steam cloud explosion, the injection fire and the fireball fire in gas pipeline[10-11].

The existing researches on natural gas jet fire are mainly focused on the experimental study of the concentration of substance, the angle of injection and the size of voids in natural gas, and the study of fire hazard in open space. It is necessary to perform the research on the leakage of different pressure pipelines, especially the researches about this area are rare.

2. Mathematical Model

2.1 Jet Velocity Model

The characteristic parameters of natural gas jet fire are related to gas leaking velocity, and the gas leakage rate is related to gas velocity and medium pressure in the pipeline. There are different formulas for calculating the gas leakage rate at different flow rates.

When the pressure difference between the pipe inside and outside meets $P_0 - P \leq \left( \frac{2}{k+1} \right)^{\frac{1}{k}}$, the gas in the tube is sonic flow, and the flow velocity calculation formula is:

$$Q = C_d A P \left( \frac{M k}{R T} \right)^{-k+1} \left( \frac{2}{k+1} \right)^{\frac{1}{k+1}} \quad (1)$$

When the pressure difference between the pipe inside and outside meets $P_0 - P > \left( \frac{2}{k+1} \right)^{\frac{1}{k}}$, the gas in the tube is subsonic flow, and the flow velocity calculation formula is:

$$Q = C_d A P \left( \frac{2k M k}{k-1 R T} \right) \left( \frac{P_o}{P} \right)^{\frac{1}{k+1}} - \left( \frac{P_o}{P} \right)^{\frac{1}{k}} \quad (2)$$

Where $P_0$ is local atmospheric pressure, $P$ is gas pressure in pipe, $k$ is adiabatic index, $Q_0$ is leakage mass rate, $C_d$ is leakage coefficient, $M$ is gas molar mass, $T$ is gas initial temperature, $A$ is leak area, $R$ is gas constant.

The gas leakage velocity is related to the Maher number, which is related to the static pressure at the leak hole. The static pressure at the leakage hole is determined by the initial pressure of the pipeline. The formula is as follows.

$$P_c = P \times \left( \frac{2}{(k+1)} \right)^{\frac{1}{k+1}} \quad (3)$$

$$M_j = \left( \frac{k+1}{k} \times \left( \frac{P_c}{P_j} \right)^{\frac{k-1}{k}} - 2 \right) \times \left( \frac{k}{k-1} \right) \quad (4)$$

$$T_j = T \times \left( \frac{P_c}{P_j} \right)^{\frac{k-1}{k}} \quad (5)$$

$$u_j = M_j \times \left( k \times 8.314 \times T_j / M \right)^{\frac{1}{k}} \quad (6)$$

Where $P_c$ is static pressure of leakage hole, $M_j$ is Maher number, $T_j$ is leakage hole pre expansion temperature, $u_j$ is gas flow at the leak hole.

2.2 Governing Equation

FDS fire calculation follows the conservation equation of mass, momentum conservation equation, energy conservation equation and chemical reaction law.

1) Mass Conservation Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0 \quad (7)$$

Where $\rho$ is leakage gas density, $t$ is the simulation time, $\nabla$ is Laplace operator, $u$ is leakage of gas
velocity vector.

2) Momentum Conservation Equation

\[ \frac{\partial}{\partial t}(\rho u) + \nabla \cdot \rho uu + \nabla p = \rho f + \nabla \cdot \tau \]  

(8)

Where \( P \) is pressure, \( f \) is the external force vector, \( \tau \) is Viscous vector.

3) Energy Conservation Equation

\[ \frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho hu = \frac{\partial q}{\partial t} + u \nabla p + q - \nabla \cdot q + \Theta \]  

(9)

Where \( h \) is gas component enthalpy, \( q \) is heat release rate of gas unit volume, \( q \) is radiant heat flux, \( \Theta \) is dissipation rate.

3. Jet Fire Simulation of Different Pressure

3.1 Conditions set

We conducted multiple simulations of natural gas leakage and jet fire under 6 working conditions. When the pipe pressure value is 4.0Mpa, 2.5Mpa, 1.6Mpa and 0.8Mpa, the diameter of leak hole is 100mm, and when the pressure value of the pipe is 0.4Mpa and 0.2Mpa, the diameter of leak hole is 40mm. Set the wind speed at 2m/s and the pipeline is steel pipe. Since the gas injection tends to be stable in 5s, the simulation time 50s is sufficient to show the basic characteristics of the fire injection. Two hypotheses are made for the injection of pipeline gas leakage, one is that gas leaks and burns, the injection hole at the top of the pipeline and ejection of gas without any barriers, the other one is that the gas leakage is continuous leakage.

3.2 Flame Geometry

The simulation results show that the jet fire propagation distance is long at the beginning of leak, and then the distance gradually attenuates to an unstopped pulsation range. The larger the pipe pressure is, and the wider the flame contour is, and the more obvious the flame pulsation is. When the pipe pressure is greater than 0.4Mpa, the leakage hole becomes larger, and the leakage rate of gas increases exponentially. The combustion consumes a large amount of air around a wide range of the leakage. The flame contours of X direction and Y direction of 40mm leakage at 0.4Mpa and 100mm leakage at 0.8Mpa shows as Figure 1.

![Flame contour at 0.4Mpa](a)

![Flame contour at 0.8Mpa](b)

Figure 1: Flame contour at 2 different pressure

3.3 Temperature Analysis

Through temperature analysis, there is a small increase about temperature of the gas jet center near the leakage hole, and no obvious combustion phenomenon. The reason is that injection velocity of the gas at the hole is too high, the ejected gas is not sufficiently mixed with the air in an instant, and the internal oxygen concentration of the injection stream does not reach the range of combustion concentration.

The speed flow field is obviously at the jet center near the leakage. Gas velocity decreases gradually in flow field, and because of the Buoyancy and air resistance, the velocity of the gas will
gradually decrease to 0m/s after a certain distance. When the pipeline pressure increases, the more obvious the velocity field of gas leakage is, the longer the time required for the velocity to drop to 0 m/s. The temperature and velocity distribution of the x-z axis of the leakage center at 0.8Mpa are shown as Figure 2.

![Temperature monitoring](image1)

![Velocity monitoring](image2)

**Figure 2: Temperature and velocity distribution at 0.8Mpa**

3.4 Temperature Analysis

Through monitoring the thermal radiation of fire by 50 seconds, we found that heat flux in the simulation first reached a peak, and then gradually decreased and fluctuated within a certain range. As the pressure of pipeline increases, the fluctuation of thermal flux become obvious, and thermal flux fluctuates in a large range. The heat flux monitoring results of the pipeline under 0.2Mpa and 0.4Mpa at the distance of 12m of the leakage hole is shown as Figure 3.

![The heat flux at 0.2Mpa](image3)

![The heat flux at 0.4Mpa](image4)

**Figure 3: Heat flux monitoring results**

The leakage of combustible gas is greatly influenced by the diameter of leakage hole. The thermal flux value of two different leakage hole dimensions is analyzed as follows.

1) Diameter of leakage hole is 40mm

The pipeline pressure is 0.2Mpa and 0.4Mpa, and the leakage hole is 40mm. The thermal flux values of the same distance of the leakage hole are measured respectively. The statistical results are shown in Tab. 1.

| Distance Pressure | Calorimeter value under 0.2mpa and 0.4mpa /kW.m⁻² |
|-------------------|---------------------------------------------------|
|                   | 7m       | 8m       | 9m       | 12m      | 16m      | 18m      | 28m      |
| 0.2Mpa            | 300      | 220      | 151      | 37.1     | 13.2     | 9.35     | 2.19     |
| 0.4Mpa            | 420      | 300      | 210      | 54.4     | 26.4     | 19.6     | 8.72     |

As the distance between the monitoring point and the leakage hole increases, the heat flux gradually decreases. The relation curve of the jet heat flux and leakage hole distance is shown as Figure 4. It can be seen that the distance between the thermal flux value and the leakage hole is exponential. When the distance increases, the value of the heat flux decreases rapidly.
Figure 4: Relation between heat flux and hole spacing

Under the same leakage hole condition, the thermal radiation value increases along with the increase of pipe pressure in the same distance of the leakage hole. With the increase of leakage hole distance, the heat flux difference between the two pressure conditions increases, the curve is shown as Figure 5. It can be seen from the figure that the distance between the heat flux value and the leakage hole has a hyperbolic exponential relation. When the distance from the leakage hole is small, the heat flux value is large, and as the distance increases, the heat flux decreases obviously, and the decrease margin become small and stable.

Figure 5: Variation of heat flux difference

2) Diameter of leakage hole is 100mm

When the pipeline pressure is equal or greater than 0.8Mpa, diameter of leakage hole is 100mm and the pipeline pressure is 0.8m, 1.6Mpa, 2.5Mpa and 4Mpa. The jet fire heat fluxes are measured at the same discharge position. The result is shown as Fig. 6. The relation between heat fluxes values and leak spacing is exponential. With the increasing of distance, heat flux values first decrease greatly, and then decline rate becomes small, eventually, the heat flux gradually close to a stable value. The variation trend of heat flux is consistent with the increase of pipeline pressure from 0.2mpa to 0.4Mpa.

3.5 Hazard Analysis

The heat flux value is used to determine the standard value of heat radiation to personnel injury, by comparing and analyzing the position of the critical value, we found that the variation of thermal radiation simulation value is consistent with the trend of the damage radius. The figure 7 shows that near 0.8Mpa, as the pressure increase, the pipeline damage radius increase sharply, mainly due to increase size of leakage hole, leading to larger thermal radiation intensity, radiation scope and the damage radius of the combustion. When the pipeline pressure is greater than 0.8Mpa, leakage hole size maintains consistent, leakage rate of quality for the quality of pipeline pressure control rate, jet heat radiation damage radius increases with the increase of pressure pipeline is basically linear relation.
4. Conclusions

By using FDS software to simulate jet fire under the different pipeline pressure, we analyzed the influence law of pipeline pressure on characteristics of jet fire and personnel injury radius, including analysis of jet fire flame pulsation, temperature and radiation characteristics. The main conclusions are as follows:
(1) Jet fire flame geometry size was affected by the pipeline pressure. When diameter of leakage hole is fixed, the larger the pipeline pressure is, the larger the flame propagation distance of the jet flame is, the more obvious the flame pulsation is, and the more obvious and formation of the contour.

(2) When the pipeline pressure is different, the flame temperature distribution is different. With the increase of the pipeline pressure, the flame high temperature influence area expands, and the flame pulsation phenomenon is more obvious.

(3) The leakage rate of combustible gas is affected by the diameter of leakage hole, and the heat flux value is exponential in relation to the spacing of the leakage hole. The variation trend of thermal radiation value and damage range is consistent under different pipeline pressure. According to the results of hazard analysis, as the pressure of the pipeline increases, the radiation of the jet hot radiation increases the hazard range of the personnel.

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