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Research Article

Numerical Simulation of Gas Diffusion in Overhead Natural Gas Pipeline Leakage

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Abstract: The leakage of natural gas pipeline brings threat to people's safety and social stability. Gas diffusion plays an important role in detecting pipeline leakage. Diffusion model of overhead natural gas pipeline leakage was established, and diffusion process was analyzed numerically with different leakage locations and different leakage velocities. The results show that the diffusion concentration of natural gas on the ground is high when the leaking location is on the bottom. However, the diffusion concentration of natural gas on the ground is low when the leaking location is on the top. Distribution of natural gas concentration is conical when pipeline is leaking at high speed. When pipeline is leaking at medium speed, there are great differences of natural gas concentration in different heights of vertical direction. Natural gas diffusion concentration is smaller when pipeline is leaking at low speed, and there is obvious backflow around the jet beam.
Keywords: Natural gas pipeline; Leakage location; Leakage velocity; Numerical simulation.

INTRODUCTION

As a kind of efficient, high quality and clean energy, natural gas has been widely used in most developed countries. With "west-east gas pipeline project" putting into use, natural gas plays a key role in adjusting energy structure and improving the environmental conditions in our country. Pipeline transportation is the main way, but pipeline goes across a wide area, and are vulnerable to the external environment and pipeline defect itself, which leads to a mass of pipeline leakage accidents [1-4] and greatly damages to energy security and social stability.

Many factors affect natural gas pipeline leakage and diffusion, and leakage location and leakage velocity directly affect the natural gas diffusion process, so it is necessary to study these factors. For example, Jianfeng *et al.* [5] provided simulation using Fluent by applying the TOPSIS method to six RANS models (RSM, standard $k-\varepsilon$, RNG $k-\varepsilon$, standard $k-\omega$, SST $k-\omega$), the comparison result shows that the standard $k-\varepsilon$ model was the best suitable model under the simulation of heavy gas dispersion for hill-shaped terrains. Ma *et al.* [6] built the blowout accident model based on real topography, and analyzed gas dispersion based on simulation results conducted from two aspects, height and dispersion time, the data demonstrated that CFD technology can be an effective aid to describe the process of gas dispersion and also predicted the tendency of gas distribution. Qi *et al.* [7] provided the prediction results of downwind gas concentrations close to ground level were in approximate agreement with the test data. Fu *et al.* [8] established overhead pipeline leakage and diffusion control equations, and analyzed that the leakage velocity and wind speed impact on the natural gas diffusion law, finally got the methane explosion limit range to determine the best rescue time. Gao et al. [9] numerically simulated high sulfur overhead natural gas pipeline leakage, and analyzed the effect of the wind, gravity, leakage velocity and delivery pressure on pipeline leakage and diffusion, the results showed that different factors had different influence on natural gas diffusion.

According to the current research at home and abroad, this paper firstly viewed different leakage locations of natural gas pipeline leakage and diffusion as the research object, then different leakage velocities was viewed as the other research object, overhead natural gas pipeline leakage and diffusion model was established, and the process of that was analyzed numerically with different leakage locations which included the top leakage, bottom leakage and lateral leakage, then with different leakage velocities which included the high-speed leakage, medium-speed leakage and low-speed leakage when the leakage location was on the top of natural gas pipeline.

THEORETICAL MODEL

1 Natural gas pipeline leakage and diffusion control equation

Natural gas pipeline leakage process can be regarded as free jet, gas in the process of leakage follows the mass conservation, momentum conservation and energy conservation. Assuming the gas diffusion process doesn't produce chemical reaction, using multi-component material migration model. At the same time, assuming that satisfy the stationary flow, and the flow is turbulent. Modified Realizable model of standard $k-\varepsilon$ model [10-13] was used. After hypothesis, natural gas pipeline leakage and diffusion control equation was shown below:

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho u_j}{\partial x_j}=0 \quad (1)$$

where ρ denotes gas density, kg/m^3; u_j is the velocity component along j direction, m/s; x_j is the transmission distance along j direction, m.

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu_t\frac{\partial u_i}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left(\mu_t\frac{\partial u_j}{\partial x_i}\right)+(\rho-\rho_a)g_i \quad (2)$$

where x_i is the transmission distance along i direction, m; u_i、u_j is the velocity components along i、j directions, respectively, m/s; P is the pressure, Pa; μ_t is turbulent viscosity, kg/(m·s); ρ_a is air density, kg/m^3; gi is the component of gravitational acceleration along i direction, m/s^2.

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho u_j T)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_T}\frac{\partial T}{\partial x_j}\right)+\frac{c_{pv}-c_{pa}}{c_p}\left[\left(\frac{\mu_t}{\sigma_c}\right)\frac{\partial\omega}{\partial x_j}\right]\frac{\partial T}{\partial x_j} \quad (3)$$

where T is temperature, K; σ_T is surface tensile stress, Pa; c_{pv} is leakage gas specific heat at constant pressure, J/(kg·K); c_{pa} is air specific heat at constant pressure, J/(kg·K); c_p is mixed gas specific heat at constant pressure, J/(kg·K); σ_c is surface compressive stress, Pa; ω is component quality fraction.

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j\omega)=\frac{\partial}{\partial x_j}\left(\mu_t\frac{\partial\omega}{\partial x_i}\right) \quad (4)$$

$$\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left(\mu_t+\frac{\mu_a}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-\gamma_M+S_k \quad (5)$$

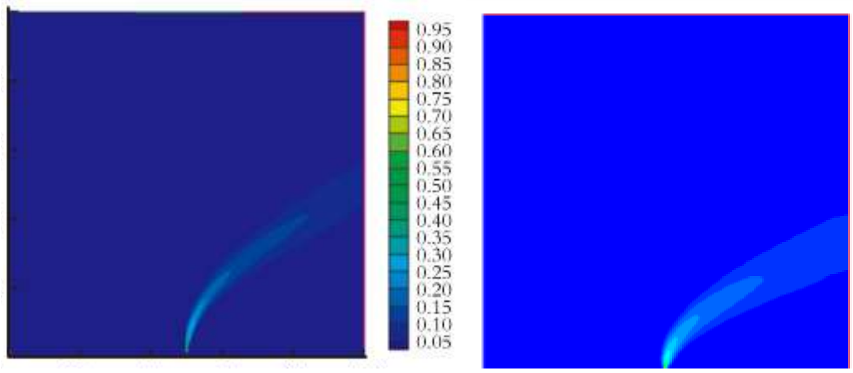
where G_k is turbulent flow of energy for an average velocity gradient producing; G_b is turbulent flow energy for buoyancy producing; γ_M is the expansion caused by fluctuations in the compressible turbulent dissipation; $\gamma_M=2\rho\varepsilon M_t^{\ 2}$,M_t is the turbulent Mach number, $M_t=\sqrt{\frac{k}{\alpha^2}}$, α is sound velocity; S_k is user-defined conditions; μ_a is air turbulence viscosity, kg/(m·s).

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu_t+\frac{\mu_a}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{U_\varepsilon}}+C_{12}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \quad (6)$$

where C_1、C_2、σ_k、σ_ε are transmission dissipation constants; S_ε is user-defined conditions; ρ is controlled by compressible gas state equation, $\rho=\frac{P}{RT\left(\sum_{i=1}^{m}\gamma_i/M_i\right)}$ (R is gas constant, i is the species number of transmission species) ; C_{12}、$C_{3\varepsilon}$ are empirical constants, $U_\varepsilon=1$。

2 Model validations

Using the example of literature [10] verify the model in this paper. The simulation space was 100m×100m, the temperature of natural gas in the pipeline and environment were 300K, the environmental pressure was a standard atmospheric pressure, wind velocity was 5m/s, the diameter of leak hole was 0.1m, the height of leaking pipeline from ground was 0.8m, and leakage velocity was 100m/s. In simulation space, left boundary was inlet of wind velocity, both top and right boundary were pressure outlet and non-backflow, and ground and walls of pipeline non-leaking direction were wall boundaries. Fluent software was used to solve the model, and the calculation results compared with the literature was shown in figure1.



(a) (b)

Fig 1: Results of natural gas pipeline leakage and diffusion (a: the literature; b: this paper)

Figure 1 show that the model calculation of natural gas leakage and diffusion clouds and literature results were basically identical, thus it proved the correctness of the model and solving method in this paper.

ANALYSIS OF NUMERICAL RESULTS

This example simulation space was 110m×120m, the diameter of pipeline was 700mm, the height from ground was 10m, leak hole was circular and the diameter was 50mm, the temperature of natural gas in the pipeline was 298.15K, leakage velocity was 626.1m/s, environmental average temperature was 288.15K, there was no wind, the environmental pressure was 1.013×10^{5}Pa. Air density was 1.225kg/m^3, viscosity was 1.789×10^{-5}Pa·s, ratio of specific heats was 1.3, acceleration of gravity was 9.81m^2/s. Methane was the main component of natural gas, so natural gas was viewed as methane in the process of calculation. Methane density was 0.668kg/m^3, dynamic viscosity was 10.87×10^{-6}Pa·s, kinematic viscosity was 14.5×10^{-6}m^2/s, specific heat at constant pressure was 1.545 J/(m^3·k), adiabatic exponent was 1.309. In simulation space, top, left and right boundaries were pressure outlet, and ground and walls of pipeline non-leaking direction were non-slip wall boundary. Pipeline was on the flat ground and there were no obstacles, soil didn't absorb natural gas and its reflectivity was 0.4.

Meshing with triangular grid, encrypt the grid and near the leak hole. Conditions and engineering requirements would be considered to sparse grid. Fluent software was used to simulate natural gas pipeline leakage and diffusion process, which included the upper leakage, bottom leakage and lateral leakage. Then natural gas concentration distribution was shown in figure2, figure 3, and figure 4.

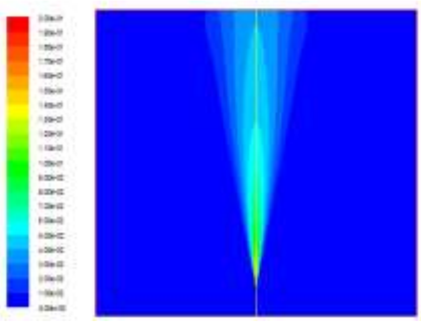


Fig. 2: results of pipeline leakage and diffusion (upper leakage)

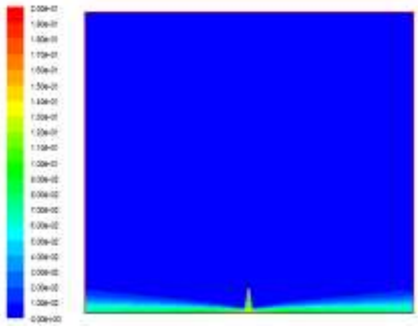


Fig. 3: results of pipeline leakage and diffusion (bottom leakage)

Fig.2 describes that the results of natural gas diffusion when leakage location was on the upper of pipeline. It could be seen that natural gas sprayed from leak hole and formed jet flow with moving up. Natural gas free diffusion let itself stable, natural gas concentration distribution was symmetrical, and was highest in the center of jet. Because of a large leakage velocity and methane was lighter than air, natural gas kinetic energy and air buoyancy dominated gas diffusion, natural gas spread outward after entering the atmosphere, and mixed air gradually. Near the leakage hole, there was high natural gas diffusion concentration, but a small scale. With the height of jetting increasing, natural gas diffusion concentration decreased, and the diffusion scale was conical, at the same time, vertical diffusion distance of natural gas was greater than the horizontal diffusion. It could be seen from Fig.3 that when leakage location was on the bottom of pipeline, natural gas sprayed from leak hole and formed jet flow with moving down. Due to a large leakage velocity and the height between leakage and ground was 10m, when natural gas reached the ground, soil didn't absorb natural gas, and natural gas kinetic energy dominated the diffusion of gas, and spread around the ground. Compared with the upper leakage, ground gathered high concentration natural gas under the bottom of leak hole. Natural gas spread gradually and diffusion scale was larger, but gas concentration was smaller. And horizontal diffusion distance of natural gas was greater than the vertical diffusion. It could be seen from Fig.4 that when leakage location was on the lateral of pipeline, natural gas sprayed from leak hole and formed jet flow laterally. Natural gas had a right leakage velocity, and diffused on the right of pipeline. Near the leakage hole, there was high natural gas diffusion concentration, but a small scale. As the diffusion of gas, horizontal diffusion distance of natural gas was larger and larger, and was greater than vertical diffusion clearly. Compared with the bottom leakage, there was high concentration natural gas near the ground, but diffusion scale was less than the bottom leakage. Free diffusion of natural gas on the left of pipeline led to small gas concentration.

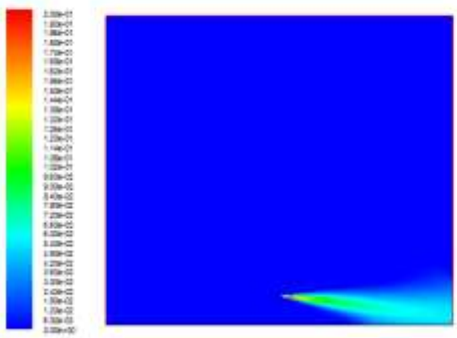


Fig. 4: results of pipeline leakage and diffusion (lateral leakage)

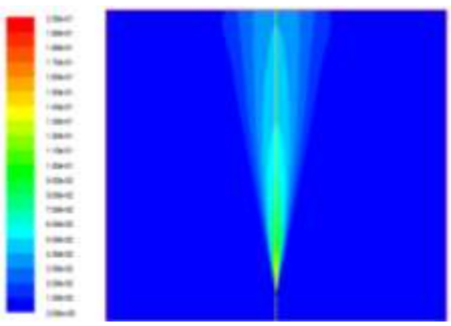


Fig. 5: natural gas diffusion concentration (high-speed leakage)

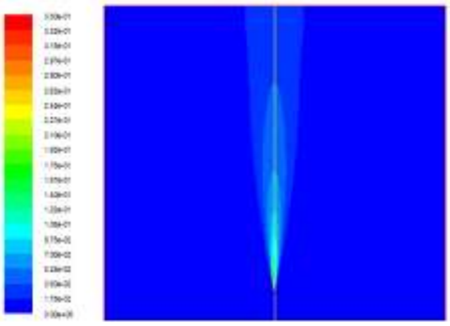


Fig. 6: natural gas diffusion concentration (medium-speed leakage)

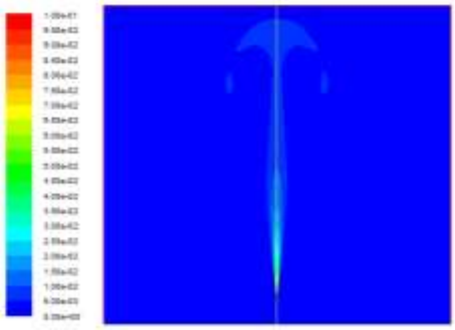


Fig. 7: natural gas diffusion concentration (low-speed leakage)

Subsequently, fluent software was used to simulate the process of natural gas pipeline leakage and diffusion, which included high-speed leakage, medium-speed leakage and low-speed leakage. Then natural gas diffusion concentration was shown in figure 5, figure 6, and figure 7.

Fig. 5 describes that natural gas diffusion concentration when pipeline was leaking at high speed (leakage velocity for 626.1m/s). It could be seen that natural gas sprayed from leak hole and formed jet flow with moving up. At the instant of jet, natural gas had great momentum, controlling the diffusion of gas. Near the leak hole, there was high natural gas diffusion concentration, natural gas mixed with air in the process of diffusion, with the increase of vertical diffusion distance, horizontal diffusion distance was also increasing, but natural gas concentration decreased. It could be seen from Fig.6 that natural gas diffusion concentration was lower than that of high-speed leakage when pipeline was leaking at medium speed (leakage velocity for 100m/s). Similarly, near the leak hole, there was high natural gas diffusion concentration. The trend of vertical and horizontal natural gas diffusion was same as that of high-speed, but diffusion scale was smaller than high-speed leakage. There were great differences of natural gas concentration in different heights of vertical direction; the distribution of natural gas diffusion concentration was symmetrical. And it could be seen from Fig.7 that pipeline was leaking at low speed (leakage velocity for 5m/s), the smaller kinetic energy of natural gas and air buoyancy controlled gas diffusion near the leake hole when natural gas sprayed from leak hole. Natural gas diffusion scales in the vertical and horizontal directions were obviously lower than that of medium speed. Natural gas diffusion concentration was generally small, only in the leak hole, gas diffusion concentration was large, and there was obvious backflow around the jet beam.

CONCLUSION

Overhead natural gas pipeline leakage and diffusion model was established, and natural gas pipeline leakage and diffusion process was analyzed numerically with different leakage locations and different leakage velocities, the conclusions were shown below:

(1) Leakage locations of natural gas pipeline had an effect on gas diffusion. Natural gas concentration distribution was symmetrical when the upper of pipeline was leaking, and natural gas concentration was largest in the center of the jet. The ground under the bottom of the leak hole gathered a plenty of natural gas when the bottom of pipeline was leaking. Near the leak hole, natural gas has high concentration but a small diffusion scale when the lateral of pipeline was leaking.

(2) Leakage velocities of natural gas pipeline had an effect on gas diffusion. Distribution of natural gas concentration was conical when pipeline was leaking at high speed, and natural gas concentration was largest in the center of the jet. Distribution of natural gas concentration was symmetrical when pipeline was leaking at medium speed, there were great differences of natural gas concentration in different heights of vertical direction. Natural gas diffusion concentration was smaller when pipeline was leaking at low speed, and there was obvious backflow around the jet beam.

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