Numerical simulation on the leakage and diffusion of the natural gas of the underground pipeline in the soil

Meijuan Hu 1, He Li 1, Li Chen 2, *, Ping Xie 3, Zheju Zhang 2, Ming Yang 3, Mingze Wu 2, Qingming Zhang 2

1 State Key Laboratory of Service Behaviors and Structural Safety of Petroleum Pipe and Equipment Materials, CNPC Tubular Goods Research Institute, Shanxi, China
2 State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Haidian District, Beijing, China
3 Petrochina West Pipeline Company, Xinjiang, China

*Corresponding author e-mail: lichenme@bit.edu.cn

Abstract. For the transportation pipeline with the diameter 1.219 m and the internal pressure 3-12 MPa, the leakage and diffusion of the natural gas of the pipeline in the soil was studied by numerical simulation. First, the finite model containing both pipeline and soil was established, and the porous media was used to simulate the real soil environment. And, the leakage amount of the natural gas was calculated at the cases with different porosities, the pressures inside the pipeline and the diameters of leakage port. Based on the classical theoretical leakage model of small hole in the air and simulation results analysis, the formula of the leakage amount was modified by the soil coefficient α to be suitable for soil environment. Then, the variation trends of the diffusion concentration of methane along different directions in the soil were analyzed by simulation, the influences of internal pressure of pipeline, the diameter of leakage and the porosity of soil were also discussed. Besides, the relationship of the safety distance with time was obtained.

1. Introduction

During the transportation process of natural gas, the leakage and diffusion of natural gas are the major accident related to personnel safety, especially for the situation of high-pressure and large-diameter pipelines. Hence, the regularity of the leakage and diffusion of natural gas have been attracted the high attention of scholars.

Assuming that the flow process was isentropic adiabatic and reversible, Ahn et al. [1] established the leakage models of hole and pipe, which distinguished the differences between the critical and non-critical flow inside the pipe and at the hole, and proposed the calculate formulas of the leakage amount. Wang et al. [2] divided the accident of the transportation pipeline into three stages, i.e., leakage, diffuse, combustion/explosion, and calculated the leakage amounts of small hole, large hole and pipe by the assumption of the isentropic adiabatic flow. It was found that when the ratio d/D between with the diameters of leakage hole and pipe was smaller than 0.2, the prediction accuracy of small hole model was well; for d/D>0.8, the prediction of the pipe model was also in good agreement with the experiment.
data, and the prediction accuracy of the larger hole model was well when d/D is only between 0.2 and 0.8. Feng et al. [3] studied the effect of the pressure stability on the leakage of natural gas, and it was found that when leakage hole was enough small, the leakage did less influence on the parameters inside the pipe, so the leakage process was considered as stable. Zhang et al. [4] studied the diffusion behaviors of refined oil in soil, and the effects of different soil properties were taken in account. Li et al. [5] researched the relationship between the axial velocity and the jet distance where the leakage occurred at the aerial transportation pipeline, the effects of gravity and wind speed were also discussed.

Many great progresses have been made in the field of the leakage at aerial pipeline and the following diffusion of natural gas, but there are few reports about the leakage and diffusion of the natural gas of the buried pipelines in the soil, especially those pipelines with high internal pressure and large diameter. In this paper, the regularity of leakage and diffusion of the natural gas of the buried pipeline with high pressure and large diameter was studied using the numerical simulation method, whose results are great significance for prevention and control of leakage accident.

2. The theoretical model of the leakage of small hole

When the transportation pipelines work under the normal atmospheric condition, there is classical theoretical model for the leakage amount of small hole. Figure.1 shows the leakage of the transportation pipelines, the point 1 is the upstream of the pipeline, the point 2 is the leakage port, and the point 3 is on the central axis of the pipeline corresponding to the leakage port.

\[
Q = C_0 A P_2 \frac{2M}{nRT_2} \left( \frac{P_a}{P_2} \right)^{\frac{k}{k-1}} \left[ \left( \frac{P_a}{P_2} \right)^{\frac{k}{k-1}} - \left( \frac{P_a}{P_2} \right)^{\frac{k+1}{k-1}} \right] \tag{1}
\]

where, A is the area of leakage port, M is Molar mass, k is adiabatic index, n is the compact factor of natural gas [6], and C0 is the modified coefficient. Generally, C0 can be taken as 1.0, 0.95 and 0.90 for the different shape of the leakage port, i.e., circular, triangle, rectangle respectively.

By differentiating Eq. (1), the pressure P2c at critical flow state is:

\[
\frac{P_a}{P_{2c}} = \left( \frac{Z}{k+1} \right)^{k-1} \tag{2}
\]

Then, the leakage volume of this port is expressed as:

\[
Q = C_0 A P_2 \sqrt{\frac{Mk}{nRT_2}} \left( \frac{Z}{k+1} \right)^{\frac{k+1}{k-1}} \tag{3}
\]

Figure 1. The diagram of the pipeline leakage
3. The simulation

3.1. The finite element mode and mesh selection

Figure 2 shows the geometry model containing the transportation pipeline and the soil, whose length and wide are both 8 m, and the pipeline with diameter \( D = 1.2 \text{ m} \) is 1.5 m below the surface of the soil. The normal of the leakage port is along the Y-axis positive direction, and the location of this port is at the center of the pipeline. Due to the pressure gradient, the diffusion behaviors of gas mainly process along the Y-axis positive direction, and the diffusion along the negative direction is slow and little at initial short time. Besides, the leakage port is away 5 m from the positive boundary \((y=5 \text{ m})\), which is enough long to avoid the influence of the boundary.

![Figure 2. The 3D geometry model of the transportation pipeline and soil](image)

In order to balance the calculation accuracy and computing cost, the maximum size of element is 256 mm, as shown in Figure 3. The maximum element size of the port is 1/3 of its diameter, and the height of the boundary layer at the leakage port is growth at a ratio of 1.1 to ensure the accuracy of the simulation calculation.

3.2. The boundary condition

The transportation pipeline involved is with high pressure, whose maximum is 12 MPa. The boundary condition of the leakage port is set as the inlet of pressure, and the boundary condition of the pipeline is the solid wall, there isn’t any exchange between with inside and outside of the pipeline. The all arounds of this model are set as the pressure outlet, and the initial concentration of methane in this region is zero.

![Figure 3. The finite element for the leakage model](image)

3.3. The property parameters of soil and gas

The density of the soil is 2.416 g/cm\(^3\), and its porosities are 0.35-0.65. The compositions of the natural gas are listed as Table 1, the main component of the gas is methane accounting for >90%.
Table 1. The composition of natural gas

(a) Hydrocarbon

| Hydrocarbon | Methane Mol% | Ethane Mol% | Propane Mol% | Isobutane Mol% | N-butane Mol% | Isopentane Mol% | N-pentane Mol% | Hexane Mol% |
|-------------|--------------|-------------|--------------|---------------|---------------|----------------|---------------|------------|
| ratio       | 90.043       | 6.050       | 1.778        | 0.100         | 0.090         | 0.020          | 0.016         | 0.050      |

(b) Non-hydrocarbon

| Non-hydrocarbon | Nitrogen Mol% | Carbon dioxide Mol% |
|-----------------|---------------|---------------------|
| Ratio           | 1.1058        | 0.7474              |

4. The validation of simulation

All relevant parameters were listed in Table 2, and brought into the previous theoretical model of small hole to attain the leakage amount $Q = 0.1594$ kg/s.

For the validation of the simulation, the medium in the fluid computing region was firstly set as air, to simulate the leakage and diffusion of the gas in air. And, the simulation result of the leakage amount was 0.1752 kg/s, which differed 9.91% with the previous theoretical value. The comparison showed that this numerical simulation had good reliability.

Table 2. The relevant parameters of the leakage model at atmospheric environment

| $C_0$ | $P_2$(Mpa) | $M$(kg/kmol) | $k$ | $R$(kJ/(kmol*K)) | $T_2$(K) | $n$ |
|-------|------------|--------------|-----|-----------------|----------|-----|
| 1     | 12.28      | 17.097       | 1.3 | 8.314           | 283      | 0.784 |

5. The simulation result

5.1. Influence of void ratio

Figure. 4-7 illustrate the curves of the leakage amount with the pressure inside the pipeline and the diameter of the port at different porosity. It can be found that the leakage amount is approximately linear with the pressure, and the relation between the leakage amount and the diameters can be well described by quadratic function. Besides, the above variation rules were similar to those which the theoretical model of small hole implies.

![Figure 4](image1)

(a) The curve of the leakage amount with the pressure (a) and the diameter (b) at the porosity 0.35
According to the above analysis, the theoretical model of small hole was modified by introducing the soil coefficient $\alpha$, to calculate the leakage amount in the soil with corresponding porosity, as Eq. (4). By fitting the simulation results at the porosities 0.35-0.65, the coefficients $\alpha$ were 0.08405, 0.14437, 0.23603 and 0.4438 respectively.

$$Q = \alpha C_0 P_2 \left( \frac{2}{RT_2} \right)^{\frac{k+1}{k-1}}$$

Equation (4)

**Figure 5.** The curve of the leakage amount with the pressure (a) and the diameter (b) at porosity 0.45

**Figure 6.** The curve of the leakage amount with the pressure (a) and the diameter (b) at the porosity 0.55

**Figure 7.** The curve of the leakage amount with the pressure (a) and the diameter (b) at the porosity 0.65
5.2. *The spatial and temporal distribution of the diffusion concentration*

The leakage port in the model is taken as the origin point, the normal of the leakage port is along the positive direction of Y-axis, the vertical upward is the positive direction of Z-axis, and the direction along the pipeline is X-axis. Monitoring points were set with those coordinates as listed in Table 3, to obtain the variation of the methane concentration with time.

| No | X(m) | Y(m) | Z(m) |
|----|------|------|------|
| X-1 | 0.5  | 0    | 0    |
| X-2 | 1.0  | 0    | 0    |
| X-3 | 2.0  | 0    | 0    |
| X-4 | 3.0  | 0    | 0    |
| Y-1 | 0    | 0.5  | 0    |
| Y-2 | 0    | 1.0  | 0    |
| Y-3 | 0    | 2.0  | 0    |
| Y-4 | 0    | 3.0  | 0    |
| Z-1 | 0    | 0    | 1.0  |
| Z-2 | 0    | 0    | 2.0  |

The concentration nephogram at different moment during 100-5000 s were shown in Figure 8, and the gas diffusion behaviors in the soil were observed. It can be seen that the methane mainly diffuses in an approximately circular shape along the positive direction of the Y-axis in the early stage. When the diffusion distance exceeded the radius of the pipeline, the methane begins to diffuse along the negative direction of the Y-axis. Besides, as the time goes on, the shape of the nephogram isn’t symmetrical on the Y-axis, and has a tendency to move upwards, which is the result of the effect of the buoyancy along the positive direction of the Z-axis.

![Figure 8. The concentration nephogram of the methane concentration at different time](image-url)
Figure 9 shows the variation of the concentration with time at different monitoring points, it is found that with monitoring points being further away from the leakage port, the slope of the curve is smaller, so that the diffusion velocity is lower. When the time is less than 5000 s, the diffusion velocity along the X-axis is larger than that along the Y-axis. For the monitoring point X-1, the concentration reaches its maximum 88% at 1580 s, and keeps almost constant in the rear. However, for the point Y-1 with the same distance which the point X-1 is away from the leakage port, the concentration reaches its maximum 87% at 2800 s. Besides, for the diffusion along the Z-axis, the concentration of the point Z-1 continues to rise with the time going on, and finally reaches 73.2%, but that of the point Z-2 does less change. The average velocities of the diffusion V1 and the concentration of accumulation V2 of the points X-1 and X-2 were listed in Table 4.

The variation of the methane concentration with distance at 5000 s is shown in Figure 10, it is found that the symmetry of concentration along that X-axis keeps well, the maximum distance of the diffusion along the positive direction reaches 2.25 m, and the distance along the negative direction is -2.15 m. However, for the methane diffusion along the negative direction of the Y-axis, owing to the separation of the solid wall condition from the computational region, there are no finite element in the region (from -1.219 m to 0 m) which is inside the pipeline, so that no data of the concentration was measured. For the positive direction of Y-axis, the methane can diffuse to 1.66 m. And, the maximum distance of the diffusion along the positive direction of Z-axis can reach 2.01 m, it can be also significantly found that the distribution of concentration along Z axis isn’t symmetry, and the concentration along the positive direction is larger than that along the negative direction, which is result of the effect of buoyancy.

Table 4. The average velocities of the diffusion and the concentration of accumulation

| Pressure (MPa) | $V_1$ (m/s) | $V_2$ (%) | $V_1$ (m/s) | $V_2$ (%) |
|---------------|-------------|-----------|-------------|-----------|
| 12            | 0.033       | 0.017     | 0.006       | 0.015     |

Figure 9. The variation of the methane concentration with time at different monitoring points: (a) X-axis; (b) Y-axis; (c) Z-axis
6. The safety distance

According to the above analysis, the comparisons of the maximum diffusion distance of three directions illustrate that at the beginning of the diffusion, the diffusion velocity of the methane along Z-axis is smaller than that along the other directions. Furthermore, along the X-axis, the curve of the maximum diffusion distance of the methane concentration 5% being the critical value to explode with time is depicted using the simulation data, as shown in Figure. 11.

The safety distance is the region where the methane concentration being less than 5%. By fitting using the form of polynomials, the relationship between the safety distance X and time is obtained as below:

$$X = 4490.39t^{1/4} - 2864.33t^{1/3} + 221.73t^{1/2} - 0.06t - 2201.05$$  \hspace{1cm} (5)

![Figure 10. The variation of the methane concentration with distance at t = 5000 s: (a) X-axis; (b) Y-axis; (c) Z-axis](image)

![Figure 11. The curve of the diffusion distance of the methane concentrate 5% with time](image)
7. Conclusion

(1) The theoretical model of the leakage in air was modified by the coefficient $\alpha$, to calculate the leakage amount inside the soil with different void ratio.

(2) At the beginning of the diffusion, the gradient of the pressure and concentration at the leakage port were larger than those of the surround, so that the methane diffused with the shape of approximate sphere on the X-Y plane. When the diffusion distance exceeds the critical value, the effect of the buoyancy was more prominent, which was compared with the effect of the gradient of the pressure and concentration, so the concentration nephogram finally became asymmetric, and had a tendency to upward.

(3) By fitting the simulation data, the relationship between the safety distance with time was attained.

Acknowledgements

This research was funded by the National Key R&D Program of China with Project No.2016YFC0801204 and No.2016YFC0802101, the Scientific Research and Technology Development Program of PetroChina with Project No.2016B-3106 and the Scientific Research and Technology Development Program of CNPC with Project No.2019B-3008. Their financial support is greatly thanked by the authors.

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