Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2023, 10(2):23-31

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Study on Gas Leakage and Diffusion Law of Comprehensive Pipe Gallery Considering the Influence of Obstacles

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Abstract In order to study the influence of obstacles on the leakage and diffusion law of gas pipeline in the gas tank of the comprehensive pipe gallery, the transient model of methane leakage and diffusion in the gas pipe tank is established by using FLUENT software and methane instead of gas; Under the condition of normal ventilation, the gas leakage diffusion law of obstacles with different heights in the gas cabin of the comprehensive pipe gallery at different positions from the leakage port and the concentration change within 15s of leakage are simulated and analyzed. The results show that the gas diffuses in the air flow direction within 15s after the gas leakage, rises to a certain extent under the action of the obstacle, and will accumulate near the obstacle. The gas concentration in the downwind of the leakage position rises rapidly, and the leaked gas will reach the alarm concentration earlier above the pipe Gallery. It can be seen that the obstacle will change the movement path of the leaked gas. Among the effects of the location, height and leakage speed of the obstacle on the gas leakage and diffusion in the comprehensive pipe gallery, the location of the obstacle has the greatest impact on the gas leakage and diffusion.

Keywords utility tunnel; gas leakage; obstacle; diffusion range

Introduction

In 2015, the General Office of the State Council announced that by 2020, China will build a number of underground comprehensive pipe galleries with international advanced level and put them into operation [1]. With the construction and development of the city, the importance of the comprehensive pipe gallery has further increased, but the various disasters and threats faced by the urban comprehensive pipe gallery in China are also becoming more and more serious, especially the natural gas pipeline is included in the comprehensive pipe gallery. Once the natural gas pipeline leaks, it is very easy to cause combustion and explosion, which seriously threatens the pipe gallery and personal safety, Therefore, it is necessary to study the leakage and diffusion laws of the gas pipeline in the comprehensive pipe gallery under different conditions to prevent and eliminate this danger.

With regard to the relevant research on the leakage and diffusion of natural gas pipeline in the comprehensive pipe gallery, Wang Yuqi [2] adopted the numerical simulation analysis method to study the influence of the leakage aperture, ventilation conditions and leakage speed on the gas leakage and diffusion in the gas cabin in the comprehensive pipe gallery. Qian Xiling [3] used Fluent software to simulate the leakage and diffusion process of natural gas under different pressure conditions, and calculated the disaster response time of the alarm detector under the 7.5m protection radius to guide the design of the alarm detector. With the development of relevant research, Sun Zhenguo [4] obtained the diffusion and concentration distribution laws of methane under the influence of different barrier distribution and wind speed through simulation, which provided a basis for effectively predicting the impact range of natural gas leakage diffusion. Chen Yu [5] compared different wind speeds, analyzed the influence of the shape and slope of obstacles on natural gas leakage and diffusion through numerical simulation of leakage and diffusion of outdoor natural gas pipelines. Xue Haiqiang et al. In the further study of the gas leakage with obstacles in the integrated pipe gallery, Wan Liujie et al. [7] used Fluent software to simulate and analyze the methane concentration distribution formed at different leakage positions of the natural gas pipeline on the top of the gas tank cabin, indicating that the methane leakage diffusion law is related to the location of the leakage point, the ventilation wind speed and the obstacles in the cabin. Huang Jian [8] proposed a plate-shaped prevention and control device on the top of the integrated pipe gallery for the detection and warning of gas leakage. Gao Baobin [9] then studied its effect and the gas leakage law under the condition of installing the baffle, indicating that installing the baffle barrier on the upper part of the gas tank can improve the gas detection efficiency to a certain extent in the absence of wind.

The above research on the existence of obstacles in the gas tank of the comprehensive pipe gallery shows that the existence of obstacles changes the gas leakage diffusion and affects the distribution of the leaked gas, but there is little research on the location and height of obstacles, and there is no further research on the location and height of obstacles on the floor of the tank under different leakage conditions on the gas leakage diffusion law. Based on the above conditions, this paper conducts relevant research on the gas leakage and diffusion law under different conditions when there are obstacles on the ground of the gas cabin in the comprehensive pipe gallery, providing reference for ensuring the safe operation of the gas cabin.

Model establishment and solution

Mathematical model

The flow of fluid follows the law of conservation of mass, momentum and energy. The gas leakage velocity of natural gas is relatively large, which is affected by indoor wall and environmental factors. The leakage in the gas tank is in a turbulent state, which complies with the turbulent transport equation. The equations are applied as follows:

(1) Mass conservation equation. The mass increment in the fluid cell per unit time is equal to the net mass flowing into the cell at the same time. The mathematical equation is as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x_i} = S_m \tag{1}$$

Where:

ρ−Gas density, kg/m^3;

u−The velocity of the fluid in the x direction, m/s;

t−Flow time, s;

S_m−The increase in mass, kg/s。

(2) Momentum conservation equation. The rate of change of fluid momentum with respect to time in the microelement is equal to the sum of various external forces on the microelement, and its equation is expressed in the two-dimensional coordinate system as:

$$\frac{\partial(\rho u_x)}{\partial_t} + \frac{\partial(\rho u_x u_y)}{\partial_x} = \frac{\partial p}{\partial x} + \frac{\partial \tau_{xy}}{\partial_x} + \rho g + F \tag{2}$$

Where:

p−Static pressure, Pa;

u_x, u_y−The component of velocity on the x and y axes, m/s;

τ_{xy}−The stress tensor, Pa;

ρg−Gravitational volume force, N;

F−External volume force, N。

(3) Energy conservation equation. The increase rate of energy in the cell is equal to the net heat flow into the cell and the work done by the volume force and surface force on the cell. The equation describing it is expressed in the two-dimensional model as:

$$\frac{\partial(\rho T)}{\partial t} + div(\rho u T) = div\left(\frac{k}{C_p} gradT\right) + S_T \tag{3}$$

Where:

T−Thermodynamic fluid temperature, K;

C_p−Specific heat capacity, J/(kg·K);

k−Heat transfer coefficient of fluid;

S_T−Viscous dissipation term, Pa·s。

Physical Model

This paper takes Xuwei New Area of Jiangsu Lianyungang underground integrated pipeline gallery phase I project as the research object to conduct simulation research. The integrated pipeline corridor of Jiangsu Avenue Section in Xuwei New Area is designed as a rectangular four-cabin, including power cabin, gas cabin and two integrated cabins. The actual size of the gas cabin is 3.8m in height and 1.8m in width, and the upper surface of the gas pipeline is 0.8m away from the floor of the pipeline corridor. Due to the large simulation range, three-dimensional modeling calculation is more complicated, and natural gas leakage mainly moves along the through direction of cabin under the action of ventilation, in order to highlight the constraints of cabin ceiling wall surface, and focus on studying the concentration distribution of natural gas along the through direction of cabin, to show the diffusion law of the longitudinal section of gas cabin in the integrated pipeline corridor. Therefore, two-dimensional modeling is adopted. The results are also close to reality. Combined with the research content of Gao Baobin [9], on the premise of not affecting the simulation effect, the shape of the obstacles is set as plate shape, the height is set as 0.8 and 0.4m, and the thickness is 0.1m. The obstacles are located downwind of the leakage port, and the horizontal distance between the obstacles and the leakage port is 3, 6, 10 and 15m, respectively. According to the Technical Specifications for Urban Integrated Pipeline Corridor Engineering (GB 50838-2015), a fire prevention zone is set for every 200m in the gas cabin of the integrated pipeline corridor [10]. Therefore, 200m is taken as a fire prevention zone, and the leakage position is located in the middle of the pipeline corridor model. The simplified model is shown in Figure 1.

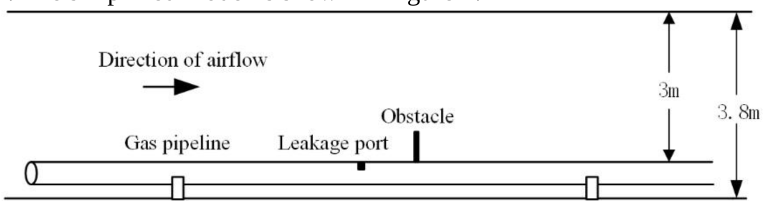

Figure 1: Simplified model of two-dimensional physics

Numerical Model

Boundary condition

(1) Size of leakage hole. The leakage of natural gas is directly related to the size of the leakage aperture. In practical engineering, due to the regular operation and maintenance of the pipeline corridor, the leakage is mainly accidental pitting sand holes and small hole leakage of cracks. In this paper, the leakage aperture of natural gas pipeline is divided according to the accident data of gas pipeline in Europe, combined with the actual leakage situation of engineering and considering the leakage conditions of natural gas pipeline in this paper, the leakage aperture is finally set as 10mm.

(2) Leakage velocity. Generally speaking, once the leakage diameter is determined, the leakage rate is proportional to the pipeline pressure. The greater the pipeline pressure, the higher the leakage rate, but the determination of the leakage rate is related to many factors. According to the research of Zhang Chenghu [11] and other scholars, the gas leakage velocity is set as 50 and 100m/s in this paper.

(3) Boundary conditions of vents. According to Article 7.2.2 of Technical Specifications for Urban Comprehensive Pipeline Corridor Engineering (GB 50838-2015), "normal ventilation and air exchange times of natural gas pipeline cabin shall not be less than 6 times /h" [10]. According to the formula provided by Hou Qingmin [12], it can be obtained that the ventilation wind speed in the comprehensive pipe gallery cabin is 1.38m/s under the condition of normal ventilation for 6 times /h.

Initial condition

To simplify the simulation process, the following assumptions were made: the cabin was filled with air, the temperature was 300K (27℃), and methane (CH_4) began to leak in place of natural gas at the initial moment; There is no chemical reaction between methane and air components in the simulation process, only component diffusion. The leakage rate remains constant throughout the process. In the early stage of leakage, methane concentration was higher when the leakage port was vertically upward [12-13]. The model was established on the upper surface of the pipeline with methane gas leaking directly upward as the working condition. The effects of air viscosity and wall roughness are ignored, and the effects of gravity and full buoyancy are considered in numerical calculation.

Solution setting

Meshing

After establishing the corresponding physical model, grid division of the model is carried out. The length of the simulated gas cabin is 200m, and the size of the leakage port is small, only 0.01m. The difference of order of magnitude between the two is about 104. The mesh mass is about 0.8 after partition.

Solve

The energy equation and k-ε model are activated, and the leakage port and vent are set as the velocity inlet and the exhaust outlet as the pressure outlet. The transient analysis time step is 0.5s, the transient analysis time step is 30 times, and the iteration operation is 15s.

Simulation results and analysis

The set value of gas detection and alarm concentration in the comprehensive pipe gallery should not be greater than 20% of the lower limit of explosion (volume fraction) [14], and the lower limit of gas explosion is set at 5% and the mass fraction is 2.82% in accordance with the property of methane. The detection and alarm concentration is 0.005 (mass fraction) [10], and the methane concentration interval in the corresponding danger area is 0.005 ~ 1.

Analysis of gas leakage and diffusion law under obstacle distribution

In order to study the influence of different distribution of obstacles on the diffusion rule of gas leakage, Fluent software is used to take detection and alarm concentration of 0.005 as the lower limit. Under the leakage speed of 50m/s and 100m/s, the diffusion of no obstacles and 0.8m height of obstacles and continuous leakage of 15s are respectively studied, as shown in Fig. 3 and Fig. 4.

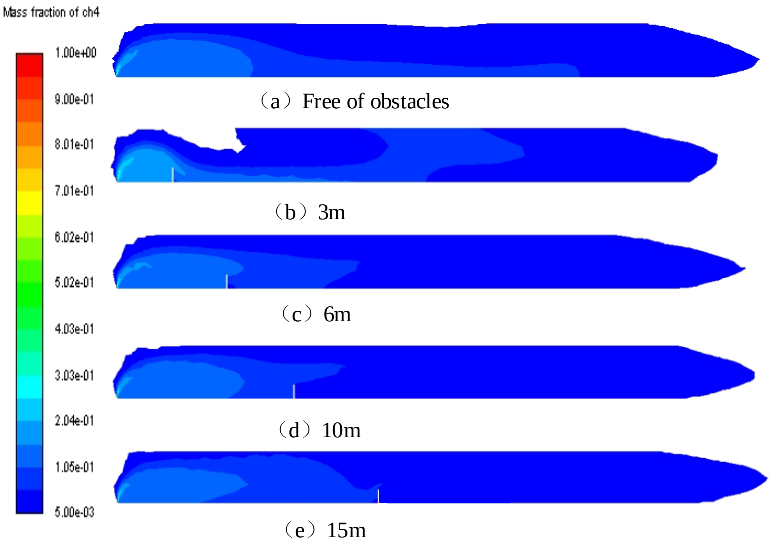

Figure 3: Dangerous concentration area of gas tank with leakage speed of 50M / s

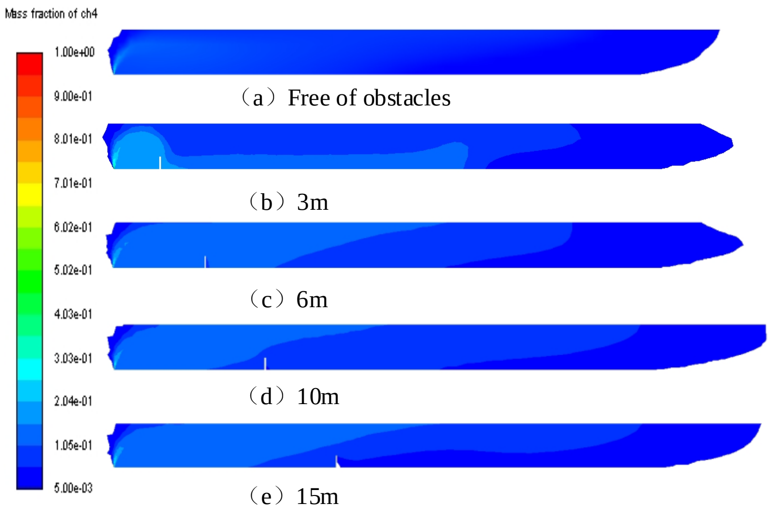

Figure 4: Dangerous concentration area of gas tank with leakage speed of 100M / s

It can be seen from Fig. 3 and 4 that methane is lighter than air when there is no obstacle and is restricted by the inner wall of the pipe corridor. The gas flow velocity at the leakage hole decreases significantly with the increase of jet height, and the leaking methane forms the injection process. When natural gas flows to the upper wall of the pipe corridor, it is blocked and gradually deviates from the jet center under the influence of ventilation, and begins to move and diffuse in the downwind direction. When the methane leakage velocity is 100m/s, the danger area formed is longer and the concentration is higher than 50m/s.

After the obstacle is added, the methane concentration is more obvious at 3m and 6m away from the leakage hole. A high concentration area is formed between the obstacle and the leakage hole, and a small safety area will appear on the upper part of the leeward area of the obstacle. With the passage of leakage time, methane is close to the floor of the pipeline corridor, forming a clumpy accumulation area at the bottom of the duct corridor under the obstacle, and the dangerous area with higher concentration is slightly larger than that without obstacle. Then the methane gas moves to the top of the cabin, and the gas concentration presents stratified distribution. This is because when the gas flows through the obstacle, boundary layer separation will occur at the front and rear of the obstacle, and negative pressure area will appear at the front and rear, attracting the surrounding fluid into the negative pressure area and forming a vortex. The negative pressure zone generated at the front of the obstacle will attract the leaking gas to attach to the obstacle; The negative pressure zone generated behind the obstacle will attract the methane gas flowing through to the lower part of the gas compartment, causing the leakage gas to settle and increasing the concentration of the leakage gas.

When the distance of the obstacle exceeds 6m, the obstructed effect of the leaking gas in the diffusion process is weakened. Part of the gas accumulates near the obstacle, while the other part of the gas moves over the obstacle to the downwind of the cabin. In addition, due to the obstruction of the obstacle and the increase of the leakage amount, the methane is raised downward to the top of the pipe gallery under the action of ventilation. The methane leakage velocity of 100m/s forms a danger zone with higher concentration than that of 50m/s, and extends downwind, increasing the danger of this zone.

In short, compared with no obstacles, the presence of obstacles makes the gas concentration in the area in front of them higher and increases with the increase of leakage velocity. Obstacles change the diffusion path of leaking gas, and the distance between the obstacle and the leakage port has a linear relationship with the influence of the obstacle on gas leakage diffusion. The closer the obstacle is to the leakage position, the greater the influence of the obstacle on gas leakage diffusion.

Analysis of gas concentration under different distribution of obstacles

According to the requirement that the space between combustible gas detectors in domestic gas tanks should not be greater than 15m, and according to the Technical Standard for Monitoring and Alarm System Engineering of Urban Integrated Pipe Gallery (GB/T 5124-2017), combustible gas detectors should not be installed more than

0.3m away from the top of the cabin [14], 15m away from the leakage position. A monitoring point was set at a height of 2.8m to explore the change of methane concentration at this position after continuous leakage for 15s.

In order to explore the influence of different obstacle sizes on the distribution of leaking gas, the heights of obstacles are set as 0.8 and 0.4m respectively. Under normal ventilation conditions, when the leakage velocity is 50m/s, the methane concentration changes at different monitoring points of obstacles are shown in FIG. 5 and FIG. 6.

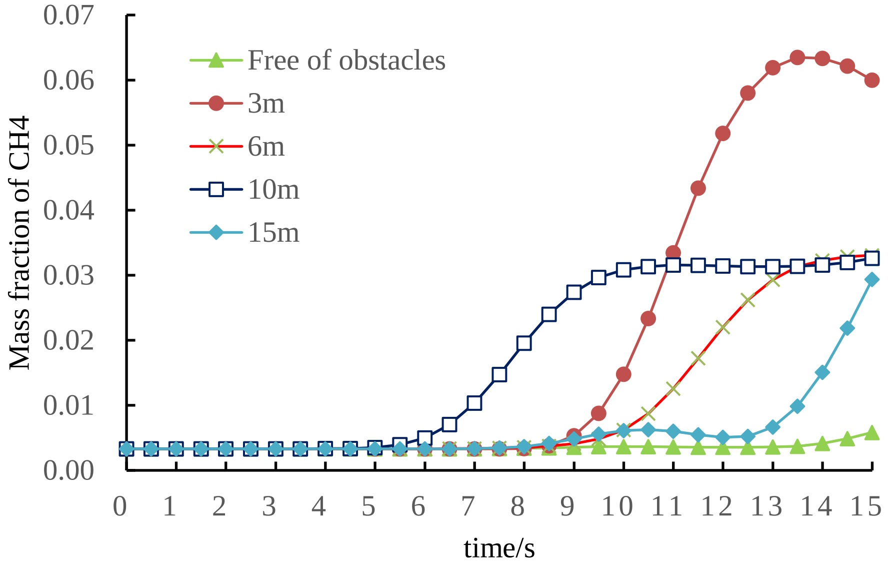

Figure 5: When the height of the obstacle is 0.8m and the leakage speed is 50M / s, the methane concentration at the detection point changes

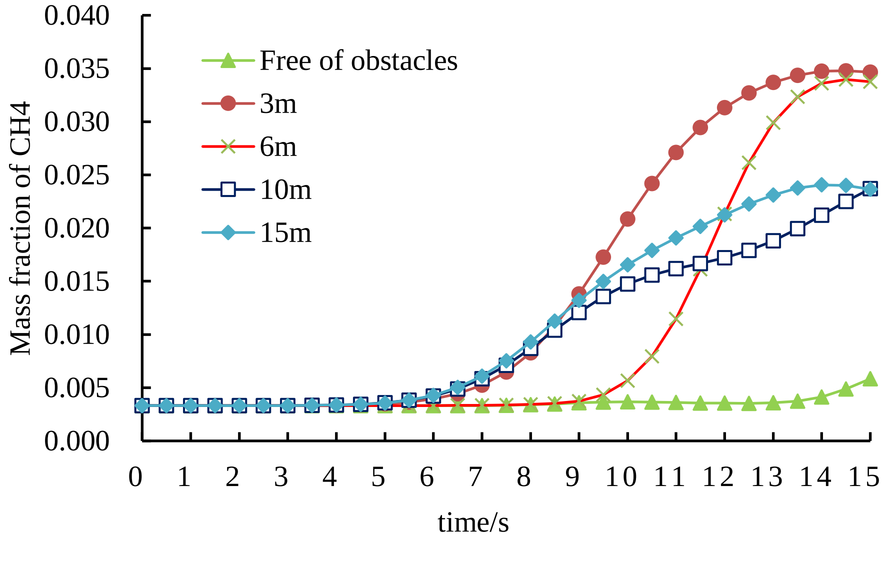

Figure 6: When the height of the obstacle is 0.4m and the leakage speed is 50M / s, the methane concentration at the monitoring point changes

According to Figure 5 and 6, when the leakage velocity is 50m/s, the alarm time of the leaking gas without obstacles is 14.5s. Ventilation has a significant dilution effect on the leaking gas, and the methane concentration is relatively low for a long time. When the height of the obstacle is 0.8m, the alarm time of the leakage gas is 8.5, 9.5, 6 and 9s when the distance from the leakage port is 3, 6, 10 and 15m. When the barrier is 3m away from the leakage port, the maximum concentration of the leaking gas is 0.063 (mass fraction). When the barrier is 0.4m high, the gas leakage alarm time is 7, 9.5, 6.5 and 6.5s when the distance is 3, 6, 10 and 15m from the leakage port. Compared with the two obstacles of different heights, the alarm time of methane detector was roughly similar. When the barrier is 10m away from the leakage port, the alarm time is the shortest.

Similarly, when there is no obstacle, the height of the obstacle is 0.8 and 0.4m, and the normal ventilation condition, the leakage speed is 100m/s. Methane concentration changes, as shown in Fig. 7 and 8.

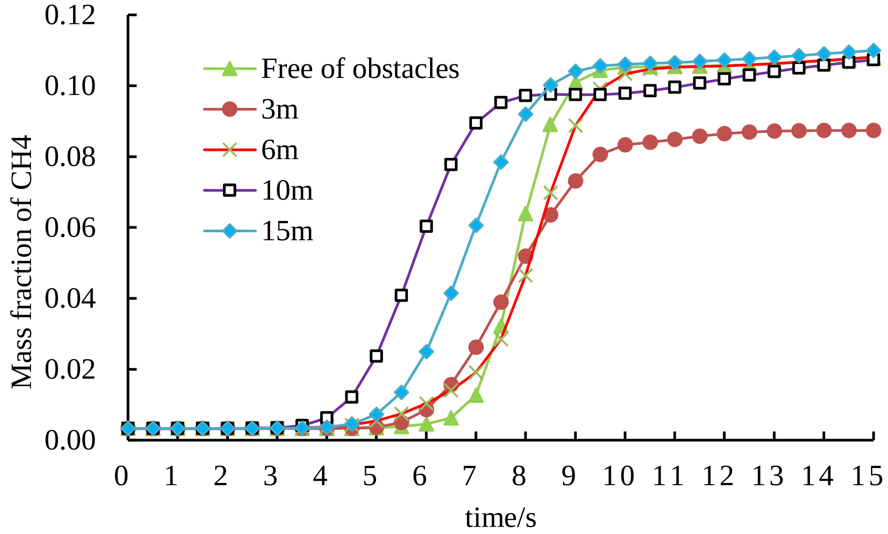

Figure 7: When the height of the obstacle is 0.8m and the leakage speed is 100M / s, the methane concentration at the detection point changes

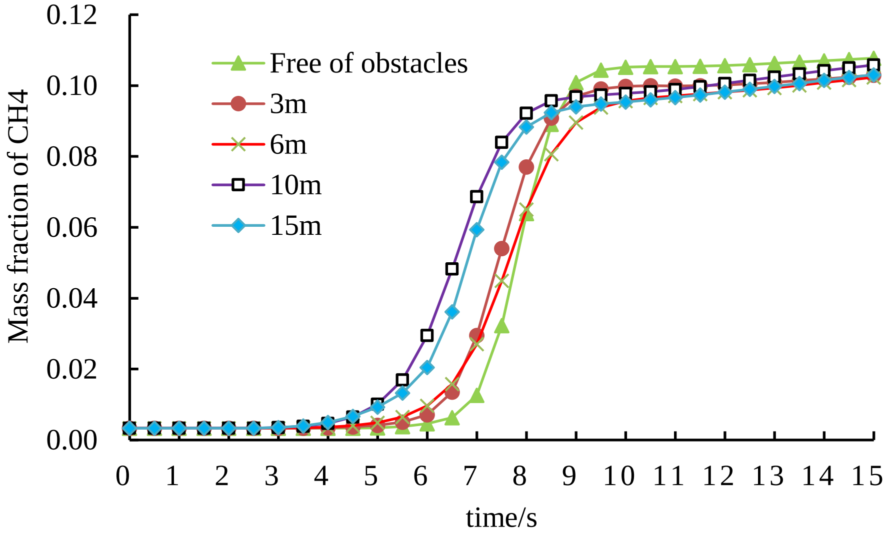

Figure 8: When the height of the obstacle is 0.4m and the leakage speed is 100M / s, the methane concentration at the detection point changes

According to Figure 7 and 8, when the leakage speed is 100m/s, the gas leakage alarm time is 6s without obstacles. When the height of the obstacle is 0.8m, the maximum concentration of the leaking gas is 0.108 (mass fraction) due to the increase of the leakage amount. When the obstacle is 3, 6, 10 and 15m away from the leakage port, the alarm time of the leaking gas is 5.5, 5, 3.5 and 4.5s, respectively. When the height of the obstacle is 0.4m, the alarm time of the leakage gas is 5.5, 5, 4 and 4.5s when the distance of the obstacle is 3, 6, 10 and 15m from the leakage port, respectively, and the maximum concentration of the leakage gas is 0.105 (mass fraction).

To sum up, compared with the situation without obstacles, the presence of obstacles changes the movement path of the leaking gas, so that the methane concentration at the position of the methane detector can reach the alarm concentration earlier, so as to give an earlier alarm. This also provides a thinking direction for improving the detection efficiency of the methane detector. From the perspective of the influence of the height of the obstacle, the decrease of the height of the obstacle also changes the methane diffusion path. However, when comparing the alarm time of the leakage gas caused by the obstacle of different heights, there is little difference between the two. However, when the height of the obstacle is 0.4m, the alarm time of different positions is closer. From the position of obstacles, the influence of obstacles at different positions on methane diffusion gradually tends to be consistent under the same conditions. Moreover, according to the curves of the four positions, it can be seen that when the obstacles are 10m away from the leakage port, the change of the movement path of the leaking gas caused the methane concentration at the methane detector to reach the lower detection limit earlier. From the perspective of the leakage velocity, under the same conditions, the high leakage velocity will shorten the alarm time of the leaking gas, and the methane concentration will be higher. However, when a small amount of gas leaks, the obstacle will have a more obvious effect on the improvement of the concentration and shorten the alarm time.

Conclusion

(1) The effects of obstacles on gas leakage and diffusion are mainly manifested as blocking and lifting effects. The blocking effect causes combustible gas to deposit near the obstacles and form clumping accumulation areas with high concentration, which increases the possibility of dangerous accidents in this area. Lifting causes the leaking gas to jump upward along the barrier. The distance between the obstacle and the leakage position has an inversely proportional effect on the gas leakage and diffusion. In the case of obstacles, the increase of leakage amount (leakage velocity), in the same time, it is easier to form a large range of higher concentration of dangerous areas.

(2) The presence of obstacles makes the gas above the cabin reach a higher concentration earlier, so the methane detector can detect the existence of leaking gas earlier, and this effect is more obvious when the gas leakage is small. Therefore, it can be considered to improve the detection effect of methane detector in the integrated pipeline corridor by reasonably placing obstacles of a certain height without affecting the normal ventilation and maintenance operation of the pipeline corridor.

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