Study on Gas Diffusion in Fire Working Areas of Oil and Gas Pipelines Based on Temperature Difference

Dengfeng Zheng, Zhongan Jiang,* Jing Qu, Mingxing Zhang, Xiaoyan Hao, Guoliang Zhang, Jiuzhu Wang, and Yapeng Wang*

**ABSTRACT:** When a pipeline is under fire safety work construction, the stack effect of the pipeline will increase the diffusion rate of nitrogen, reduce the oxygen content, and cause asphyxia. To prove the influence of the stack effect of the pipeline on the nitrogen movement in the pipeline and put forward effective ventilation control measures, the formation mechanism, gas diffusion law, and ventilation parameters of the stack effect of the oil and gas pipelines are studied through theoretical derivation and numerical simulation. The results show that the nitrogen concentration at the height of the breathing zone in the hot zone first increases and then decreases along the axial distance. The larger the temperature difference, the faster the diffusion speed of nitrogen in the fire safety work area, and the lower the oxygen concentration. When the temperature difference increases to 30 °C, the maximum oxygen concentration in the work area is 0.177; to control the problem of low oxygen content caused by the stack effect, three ventilation schemes are put forward. Through the analysis that installing fans symmetrically on both sides, 4 m away from the pipe opening, can effectively reduce the stack effect intensity when the optimal working wind speed of the fan is 4 m/s. The findings of this study can help in better understanding the causes of the chimney effect during pipeline fire safety work and provide theoretical basis for controlling personnel suffocation caused by the chimney effect.

**1. INTRODUCTION**

When the pipe wall is damaged, fire safety work shall be carried out to repair the pipeline. The fire safety work of oil and gas pipeline often involves nitrogen replacement, which fills the pipeline with nitrogen. Upon the opening of the pipeline, nitrogen and residual methane in the downstream of the pipeline slowly flow into the operation area. However, when the upstream seal of the pipeline is not tight, under the effect of the drop and the density difference caused by the temperature change of the gas inside and outside the pipeline, the emission speed of nitrogen and methane will be accelerated, leading to the pipe chimney effect, and improper handling will easily lead to suffocation of personnel in the operation area or explosion. Therefore, to control the harm caused by the chimney effect at the oil and gas pipeline fire safety work construction stage, the formation mechanism of the chimney effect and the relationship between gas diffusion law and natural factors are studied and analyzed. At present, scholars at home and abroad mainly study the formation mechanism of the chimney effect, the law of airflow movement, and the prevention and control measures to avoid the chimney effect. In the 1960s, two Canadian scholars, Tamura and Wilson, were the first to study the chimney effect. They measured and analyzed the pressure difference distribution and air permeability of several high-rise buildings under the chimney effect. Zhang et al., established a small-scale shaft on a similar experiment platform using a similar theory, and found that the formation mechanism of the chimney effect is mainly a combination of the pressure difference inside and outside the shaft and the buoyancy of the flue gas itself. Wang et al., elaborated the principle of the chimney effect, deduced the practical formula for calculating the pressure difference, and focused on the chimney effect and natural ventilation of low-rise buildings in summer. Cooper developed a new movement model of flue gas in the shaft according to the limitations of the traditional zonal fire model, and simulated the buoyancy driven and natural convection driven movement of flue gas in the shaft. When the

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temperature inside and outside the shaft is fixed, Klote et al. deduced the calculation formula of the neutral plane position of different shafts. Yang et al. and others, set up a dimensionless model to analyze the chimney effect. The chimney effect is generated by the hot gas in the adjacent space. Zou analyzed the hydraulic working conditions of the ventilation shaft in a residential building, studied the influence of the buoyancy generated by the "chimney effect" in the shaft on the ventilation effect at different times, and put forward a new idea of using the "chimney effect" in the shaft to improve the ventilation effect of the building. Feng et al., took a high-rise building in Xi’an as an example, and studied the influence of combined action of hot pressure and hot wind pressure on the internal air distribution of high-rise buildings. Wong et al. used the wind tunnel test and CFD software simulation to study the influence of the chimney effect on natural ventilation, and compared the experimental results with numerical simulation. Kim et al., used the numerical simulation method to study the movement law of flue gas in the elevator shaft. It was found that the movement law of the gas in the shaft was related to the Grashof number. Mercier et al. studied the flow and heat transfer of flue gas in the vertical open shaft through a 1/3 size experimental platform. Tamm et al. also studied the movement of hot gas in the shaft caused by buoyancy and pressure through experiments. Xu et al. and others, studied the neutral plane of the shaft and stairwell, and established the neutral plane prediction model considering the heat transfer between the flue gas and wall. Song et al. studied coal mine fire. It was found that the chimney effect is the self-sustaining mechanism of gas supply to coal mine fire when the U-channel is used to induce natural ventilation. Wang et al. analyzed the characteristic temperature field of inclined shaft fire caused by the chimney effect when discussing the influence of the tunnel width and slope on the roof temperature distribution under fire conditions. Zhou studied the chimney effect of super high-rise buildings under air conditioning in winter through numerical simulation, and found that wind pressure can weaken the chimney effect of the elevator shaft. Chen et al. found through numerical simulation that pressurized air supply to the stairwell can meet the requirements of smoke control, and determined the return pressure coefficient of air supply by the wind speed method. Tamura et al. pointed out that the minimum value of pressure increment in the well generated by pressurized air supply to the stairwell should be equal to the maximum value of the pressure intensity of hot flue gas. Wang et al. found that when three adjacent fire doors in the stairwell were opened at the same time, the positive pressure formed in the stairwell decreased significantly.

Through the analysis of the above literature, it is found that most of the research on the chimney effect is the analysis of airflow operation law under the effect of air temperature difference in high-rise buildings, and there is no direct study on the gas diffusion law caused by the chimney effect of pipes. To comprehensively analyze the formation mechanism of chimney effect and the variation of the oxygen content in the hot work area under different ventilation modes. First, the forming process of the chimney effect is analyzed by theoretical derivation, and the strength calculation formula of a pipe chimney is deduced. Then, the ventilation parameters were simulated and analyzed, and the best ventilation mode was finally determined, which provided a theoretical basis for fan layout during construction, reducing the risk of suffocation and combustible gas fire and explosion.

2. RESULTS AND DISCUSSION

2.1. Analysis of the Gas Diffusion Law under Different Temperature Differences. When the altitude difference between the two places of the pipeline is constant, the temperature difference between the inside and outside of the pipeline has a great influence on the diffusion speed of the pipeline gas at the opening. At the same time, nitrogen, methane, and other gases enter the work pit and are affected by the temperature, which aggravates the diffusion speed. To analyze the gas diffusion law under the action of temperature in detail, according to the local temperature changes, six different temperature differences of 5, 10, 15, 20, 25, and 30 °C are selected to simulate the gas diffusion law for the pipeline fire safety work pit analysis. To directly reflect the influence of environmental temperature difference on gas diffusion, CFD-Post software was used to process the nitrogen concentration diffusion cloud graph under the effect of different temperature differences at the same time. The effect of temperature difference on nitrogen diffusion is shown in Figure 1.

It can be seen from the formation mechanism of chimney effect of oil and gas pipeline in part 2.1 of this paper that the diffusion velocity of nitrogen increases with the increase of temperature difference. The main reason is that the formation mechanism of the chimney effect of Section 2.1 oil and gas pipelines can be seen as the difference increases, the nitrogen diffusion power is strengthened. Therefore, as the temperature difference increases, the area of the nitrogen exceeding the

**Figure 1.** Cloud map of nitrogen distribution in the hot zone at different temperature differences.
standard in the fire safety work area increases. In addition, under different temperature differences, when nitrogen diffuses from the oil and gas pipeline, it diffuses in an elliptical shape.

To analyze the influence of nitrogen diffusion in the pipeline caused by the chimney effect on the personnel in the operation area, a distance of 1.2 m from the ground and 1.1 m from the pipeline was selected, and the change in nitrogen quality of this location under different temperature differences was analyzed, as shown in Figure 2.

It can be seen from Figure 2 that under different temperature differences, the nitrogen mass fraction first increases and then decreases along the axial direction of the pipeline. With the increase of the temperature difference, the peak concentration of nitrogen gradually increases, and the corresponding peak oxygen concentration gradually decreases. When the temperature difference is 30 °C, the oxygen concentration in the hot area is reduced from 0.21 to 0.177. People working in this environment are likely to suffer from suffocation, so it is necessary to improve the air quality in the fire safety work area.

2.2. Influence of Local Ventilation on the Gas Diffusion Law in the Fire Safety Work Area. 2.2.1. Determination of the Optimal Installation Location of Fans in the Fire Safety Work Area. According to the characteristics of the field operation area, three ventilation plans were selected to control the suffocation hazard of workers in the operation area caused by the chimney effect. The main purpose of the ventilation plan is to select the best power and the best installation position of the fan, so that the oxygen content in the work area reaches the operation standard, the position of the fan in the three ventilation plans is shown in Figure 3. The first plan is to install a fan on the side of the work area and
install it at a 45° angle to the oil and gas pipeline. The second plan is to install two fans on the side of the work area. The third plan is to install fans symmetrically on both sides of the oil and gas pipeline. Figure 4 shows the distribution of the flow field in the fire safety work area of oil and gas pipelines under different ventilation plans.

Figure 4. (a−c) Flow field vector distribution of the hot area in various plans.

Figure 4a shows the flow field changes in the operation area when a single fan is ventilating. When a single fan is ventilating, the airflow gradually attenuates along the way, and eddy currents are formed in some areas, which can easily cause nitrogen accumulation. Figure 4b shows the installation of two fans on one side of the operation area. It can be seen from the figure that vortices are formed in the operation area on the other side of the installed fans, which is not conducive for nitrogen removal. Figure 4c shows the flow field distribution under the action of two fans on the right side of the fire safety work area. It can be seen from the figure that, under the condition of ensuring the symmetrical and stable airflow provided by the fans, the fans on the right side can ensure relative stability of the airflow direction in the operation pit. It ensures that there is always fresh air supply in the nitrogen generation area. At the same time, the angle between the installation of the fan and the pipeline is solved. The fan provides the pressure for the left side movement of the gas phase in the flow field, which will further inhibit the nitrogen diffusion speed caused by the chimney effect.

Figure 5 shows the cloud chart of the oxygen concentration at the height of the respiratory zone in the operation area under different plans. It can be seen from the cloud chart that the oxygen content in about one quarter of the area in the operation pit has decreased to about 0.18 within one minute. This single fan air supply mode is not conducive to the formation of a stable airflow, and cannot meet the requirements of improving the oxygen content in the pit. Figure 5b shows the oxygen concentration of one side of the operation area when two fans ventilate. It can be seen from the figure that when the two fans ventilate, the oxygen concentration on one side of the fan is 0.21, which can meet the oxygen demand of the personnel when they work. However, due to the existence of eddy currents on the other side of the fan, the local oxygen concentration is reduced, and the minimum oxygen concentration is 0.06, which can easily cause suffocation of the personnel. Figure 5c shows the oxygen concentration during ventilation using double fans on the right side of the fire safety work area. It can be seen from the figure that the nitrogen content is controlled at the opening of the pipeline to the greatest extent, which basically does not cause the problem of high nitrogen concentration in the rest of the foundation pit. The problem of high concentration exists only within 0.2 m of the pipeline opening on the left side, which fully meets the operation requirements. To sum up, third plan can better control the oxygen concentration in the fire safety work area.

To visually analyze the impact of different plans on the oxygen concentration in the operation area, a position 1.2 m from the ground and 1.1 m from the pipeline is taken as the monitoring point to monitor the change trend of oxygen concentration in the operation area under different plans, as shown in Figure 6.

Figure 6. Change of the oxygen mass fraction under different ventilation plans.

It can be seen from Figure 6 that when plan one is adopted for local ventilation, the oxygen mass fraction first decreases, then increases, and then decreases along the axial distance; when plan two is adopted for local ventilation, the oxygen mass fraction first decreases, then increases, and finally tends to stable along the axial direction; and when plan three is adopted for local ventilation, the oxygen mass fraction basically does not change along the way, which approximately is the mass fraction of a straight line of about 0.22. Meanwhile, when plan one is adopted for ventilation, the oxygen mass fraction in the
area with axial distance not more than $−1.45\text{m}$ reaches the normal value of 0.21, and when the axial distance is more than $−1.45\text{m}$, the oxygen mass fraction in the area is lower than the normal value due to the eddy current, and the minimum oxygen mass fraction is 0.19; when plan two is adopted for local ventilation, the oxygen mass fraction in the area with axial distance not more than $−1.24\text{m}$ is lower than the normal value (0.18). When the axial distance is greater than $−1.24\text{m}$, the oxygen mass fraction in this area reaches the normal value. It can be seen from the change trend of oxygen mass fraction in the breathing zone in fire safety work area that plan three is superior to plan one and plan two among the three ventilation plans.

2.2.2. Simulation Analysis of the Best Power of the Fan in the Fire Safety Work Site. The above determined installation position of fan can give rise to symmetrical airflow to inhibit nitrogen diffusion under the chimney effect, weaken the chimney effect intensity, and reduce nitrogen emission speed and amount, so as to avoid suffocation caused by rapid accumulation of nitrogen, and provide fresh airflow in the fire safety work area, and discharge toxic and harmful gases along the flow field, so as to ensure site operation taking care of the health of the personnel. When the location of the fan is determined, the reasonable fan power can not only ensure air quality in the fire safety work area but also result in energy saving and emission reduction. Therefore, according to the requirements of fire safety work regulations, the environmental wind speed shall not exceed five levels (below 8 m/s), and four wind speeds of 7, 6, 5, and 4 m/s shall be simulated respectively. Figure 7 shows the change in the trend of axial and radial oxygen at the respiratory height of the workers at different wind speeds.

It can be seen from Figure 7 that when the wind speed is different, the oxygen mass fraction at the height of the breathing belt first increases and then stabilizes along the axial direction, and when the axial distance is less than $−2\text{m}$, the oxygen mass fraction increases with the increase of the wind speed, but the increase range is small, and when the axial distance is more than $−2\text{m}$, the impact of the wind speed on the oxygen mass fraction is small. At different wind speeds, the oxygen mass fraction of the breathing zone height changes approximately in a V shape along the radial direction. The closer it is to the oil and gas pipeline crossing, the lower the oxygen mass fraction is, but the area is not within the scope of the operation area. Therefore, considering minimum energy consumption, the air quality of the operation area can be guaranteed when the wind speed of the fan is 4 m/s. At the same time, to prevent very high concentration of harmful gases, environmental sensors should be arranged at the site to monitor the gas change in the operation area in real time through the equipment to ensure construction safety.21

3. CONCLUSIONS

(1) The formation mechanism of the pipe chimney effect is analyzed, and the mathematical model of the pipe chimney effect under different pipe drop is constructed.

(2) With the increase in temperature difference, the diffusion intensity of nitrogen increases gradually in the fire safety work area, the peak concentration of nitrogen increases gradually, while the corresponding peak concentration of oxygen decreases gradually. When the temperature difference reaches 30 °C, the peak concentration of oxygen decreases to 0.177.

(3) When plan one is adopted for ventilation, the oxygen mass fraction in the area with axial distance more than $−1.45\text{m}$ fails to reach 0.21. When plan two is adopted for ventilation in the fire safety work area, the oxygen mass fraction in the area with axial distance less than $−1.24\text{m}$ is less than 0.21. When plan three is adopted for ventilation, the oxygen concentration in the respiratory belt height is approximately a straight line along the way, with the value of about 0.22.

(4) Through the optimization of the ventilation plan, the best installation position is to install fans symmetrically on both sides of the oil and gas pipeline. Under this installation position, the diffusion of nitrogen to the fire safety work area can be well controlled, and only the problem of high concentration exists within the 0.2 m range of the left pipe mouth position.

(5) At different wind speeds, the oxygen mass fraction of the breathing zone height first increases and then stabilizes
along the axial direction, and changes approximately in a V shape along the radial direction. When the wind speed drops from 7 to 4 m/s, the influence on the oxygen mass fraction in the working area is small.

4. CALCULATION MODEL OF THE CHIMNEY EFFECT AND COMPUTATIONAL METHODS

4.1. Formation Mechanism of the Chimney Effect of Oil and Gas Pipeline. Xinjiang oil and gas pipeline laying has height difference, and the fire safety work area is at a high place. Assuming that the temperature in the oil and gas pipeline is \( T_s \), and the temperature outside the oil and gas pipeline is \( T_0 \), the chimney effect will be produced during the pipeline fire safety work due to the temperature difference, and the formation mechanism of the chimney effect of the oil and gas pipeline is shown in Figure 8. The pressure inside and outside the pipeline at the height is as shown in the formula\(^{22-25}\):

\[
P_s(h) = P_0 - \rho gh
\]

\[
P_0(h) = P_0 - \rho_0 gh
\]

Figure 8. Schematic diagram of the formation mechanism of the chimney effect of oil and gas pipelines.

Table 1. Boundary Condition Parameters in Numerical Simulation

| boundary conditions | parameter setting | boundary conditions | parameter setting |
|---------------------|-------------------|---------------------|-------------------|
| solver type         | pressure-based    | time                | transient         |
| energy equation     | on turbulence model| turbulence intensity| \( k-\varepsilon \) |
| inlet boundary type | pressure inlet    | gravity             | 1.3               |
| outlet boundary type| outflow           | gravity             | 9.81 m/s\(^2\)   |

Figure 9. Physical model of the hot area.
Then $\Delta P_{\phi} = (\rho_0 - \rho_s)gh$, the height difference $H$ exists as $h'$ because the local temperature makes $\Delta P_{\phi} = 0$.

When $T_0 > T_f$, \( \{ h < h', \rho_0 < \rho_s, \Delta P_{\phi} > 0 \} \), the airflow in the fire safety work area flows into the pipe.

When $T_0 < T_f$, \( \{ h < h', \rho_0 > \rho_s, \Delta P_{\phi} < 0 \} \), the airflow in the fire safety work area flows from the oil and gas pipeline to the atmosphere.

4.2. The Intensity of the Chimney Effect of Oil and Gas Pipelines. The difference in density between the inside and outside of the pipeline leads to the existence of a pressure difference, which is the main factor causing the flow of gas. The change in the density is greatly affected by the temperature. According to the principle of natural wind pressure and the law of conservation of energy, the relative negative pressure value generated by the change in the gas density inside and outside the pipeline is theoretically derived. In addition to the influence of the relative negative pressure value, the absolute atmospheric pressure difference between the upstream and downstream places is another factor that causes the gas flow in the pipeline. Oil and gas are transported from Xinjiang to Guangxi through pipelines, the transportation distance is longer, the distance between adjacent valve rooms and stations is larger, and the atmospheric pressure between the two places is significantly reduced due to the influence of the altitude drop. The change in the atmospheric pressure is the second factor driving the movement of the gas in the pipeline. Based on the above-mentioned differential pressure analysis and taking into account the factors that induce changes in atmospheric pressure, the calculation of the chimney effect strength is divided into two intervals according to the difference in the pipeline drop.

(1) When the drop is less than 100 m.

The pressure difference that induces the airflow in the pipeline is composed of two parts of the above analysis. The first part of the pressure change $P_1$ caused by the natural height drop is

$$P_1 = 101.3 - 101.3$$

\[
\left.1 - 0.0255 \times \frac{h}{1000} \left( \frac{6357}{6357 + \frac{h}{1000}} \right) \right]^{5256} 
\]

(3)

The density difference caused by temperature change, resulting in the change in the internal and external pressure difference $\Delta P$ is

$$\Delta P = \rho_s gh - \rho_1 gh$$

(4)

The calculation formula of the pressure difference $P_h$ that causes the chimney effect of the pipeline under the above two factors is

$$P_h = P_1 + \Delta P$$

$$= 101.3 - 101.3$$

\[
\left.1 - 0.0255 \times \frac{h}{1000} \left( \frac{6357}{6357 + \frac{h}{1000}} \right) \right]^{5256} 
\]

\[
+ \rho_s gh - \rho_1 gh 
\]

(5)

(2) When the drop is greater than 100 m.

Similarly, when the drop is greater than 100 m, the pressure difference that induces airflow in the pipeline also consists of the two parts of the above analysis. Among them, the calculation method of the external atmospheric pressure difference $P_1$ is unchanged, and the pressure difference caused by the temperature-dependent density change is directly obtained from the calculation equation containing the temperature change. The density difference caused by temperature change, the resulting change in internal and external pressure difference $\Delta P$ is

$$\Delta P = 0.0341K_p h \left( \frac{1}{T_0} - \frac{1}{T_1} \right)$$

(6)

where

$$K = 1 + \frac{h}{10000}$$

Therefore, the calculation formula of the chimney effect induced by the pipeline is

$$P_h = P_1 + \Delta P$$

$$= 101.3 - 101.3$$

\[
\left.1 - 0.0255 \times \frac{h}{1000} \left( \frac{6357}{6357 + \frac{h}{1000}} \right) \right]^{5256} 
\]

\[
+ 0.0341K_p h \left( \frac{1}{T_0} - \frac{1}{T_1} \right) 
\]

(7)

4.3. Simulation Analysis of Gas Diffusion in the Hot Area under the Chimney Effect. 4.3.1. Establishment of a Mathematical Model for Chimney Effect Simulation. The gas diffusion law in the fire safety work area is simulated by the component transport and $k$–$\varepsilon$ turbulence model, and the energy and mass conservation equations are used as the control equation to close. In fluid mechanics, the continuity equation, momentum equation, and energy conservation equation can be expressed by a unified equation as follows:

$$\frac{\partial}{\partial t} (\rho \phi) + \text{div}(\rho \vec{u} \phi) = \text{div}(\Gamma \text{grad} \phi) + S$$

(8)

In the formula, $\phi$ represents a certain variable, $\Gamma$ is the diffusion coefficient, $S$ is the source term, and $\Gamma$ and $S$ both correspond to a specific variable $\phi$. The four terms from left to right in eq 8 are the time term, convection term, diffusion term, and source term. Taking different $\phi$, $\Gamma$, and $S$, the corresponding continuity equation, momentum equation, and energy equation can be obtained.

Component transport equation:

$$\text{Equation}$$

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gas di

din Fluent software (American ANSYS) is used to analyze the
enter the working pit. The multicomponent turbulence model
the site picture are shown in Figure 9. After the pipeline is
establish the analysis model of pit pipe replacement according
sides of the pipeline, and the slope of the escape passage is 30
four escape passages at both ends of the work pit and both
10 m, the width of the bottom is 5.6 m, the depth is 3.6 m, and
length of the excavation bottom of the pipe replacement is tentatively set at 4 m, and the free
opened after nitrogen replacement of the pipeline. The length
disipation rate of turbulent kinetic energy and the turbulent
tensor,

\[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\partial}{\partial x_i} \right] \left[ \mu + \frac{\mu_t}{\kappa} \right] \frac{\partial u_i}{\partial x_j} + G_k - \rho e + S_k \]

\[ \frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho e u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \frac{\partial}{\partial x_i} \right] \left[ \frac{\mu + \mu_t}{\kappa} \right] \frac{\partial e}{\partial x_j} + \frac{e^2}{2} \frac{C_p}{k} - \frac{e^2}{2} \rho + S_e \]

where \( \mu_t = \rho C_{\mu_t} k^2 \), \( \rho \) is the gas density, kg/m³; \( u, v, w \) are the velocity components of the fluid velocity on the \( x, y, \) and \( z \) axes, m/s; \( m_i \) is the mass ratio of different components; and \( \Gamma_i \) is the turbulent diffusion coefficient.

The authors declare no competing financial interest.

4.3.2. Establishment of a Numerical Model and Setting up of Boundary Conditions. The formation of the chimney effect of oil and gas pipelines under the action of height differences and temperature differences mostly occurs at the site of long-distance gas pipeline replacement operation with a large drop. To replace the problematic pipeline, the pipeline is opened after nitrogen replacement of the pipeline. The length of the pipe replacement is tentatively set at 4 m, and the free ends of 3 m are to be dug out at both ends of the pipe replacement section. The diameter of the pipe is 1.2 m. The length of the excavation bottom of the pipe replacement pit is 10 m, the width of the bottom is 5.6 m, the depth is 3.6 m, and the distance between the pipeline and the pit bottom is 0.6 m, the slope factor of the pipe-changing pit is 1:0.33. There are four escape passages at both ends of the work pit and both sides of the pipeline, and the slope of the escape passage is 30°. The SOLIDWORKS Software (Massachusetts) is used to establish the analysis model of pit pipe replacement according to the size of 1:1 on site. The establishment of the model and the site picture are shown in Figure 9. After the pipeline is opened by the altitude and temperature difference, the gas enters the working pit. The multicomponent turbulence model in Fluent software (American ANSYS) is used to analyze the gas diffusion process of the pipeline under different temperature differences and the flow field in the working pit after adding local ventilation. The specific setting of parameters in the simulation analysis is shown in Table 1.
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