The effects of Air-vents’ Layouts on Behaviour and Pollution of Dust in Tunnel Construction Environment

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Abstract. Study on powder behavior is the key to dust pollution prevention and control in tunnel construction environment, using wind energy to control dust diffusion is a common and effective dust control method at present. In this paper, the numerical simulation and field measurement were used to study the powder diffusion in construction of a tunnel boring machine (TBM)-based tunnel, in which the movement and diffusion properties of the powder in the tunnel were achieved and analyzed. By adjusting the height of the exhaust vent and the secondary blowing distance (L_P), the quality of air in the tunnel was optimized. The accuracy of the simulation results was also verified by the field measurements. The results showed that when the height of the dusty return airflow (H_W) is close to that of the exhaust vent (H_E), the rock-dust concentration in the tunnel could be reduced to a certain extent. When L_P < 50 m, the primary and secondary blowing airflows could form a coupled wind field in the middle of the tunnel to limit the further backward diffusion of the rock-dust. When L_P > 50 m, the dust control air-curtain could be formed within 18.83 m away from the heading. When L_P = 60 m, the rock-dust in the tunnel was effectively controlled, and the diffusion distance of the rock-dust was less than 16.4 m as well.

1. Introduction
The first paragraph after a heading is not indented (Bodytext style). Rock-dust is a major pollutant in the underground construction process[1-2]. For a relatively enclosed environment, such as construction of a subway tunnel, the hazard will be more serious because the rock-dust cannot spontaneously and effectively exhaust from the working area during the diffusion process[3-4]. Compared with a tunnel constructed by the traditional drilling and blasting method, the rock-dust control capability is significantly enhanced in the tunnel constructed by tunnel boring machine (TBM)[5]. However, TBM uses a cutterhead to cut the surrounding rocks, inevitably leading to a large amount of rock-dust generated from the heading[6-8]. The rock-dust is carried into the working area by the airflow, which may cause the pneumoconiosis disease[9]. As more and more TBMs are applied to the construction process of subway tunnels, the number of occupational disease cases in tunneling industry is increasing year-by-year[10]. Therefore, during the tunneling process in the hard rock ground using TBM, the dust-control ventilation system is often equipped to optimize the surrounding environment and ensure a clean working environment in the subway tunnel. Therefore, it is imperative to study the ventilation system and rock-dust control in construction of a TBM-based tunnel[11-12].

The construction of a TBM-based tunnel of Qingdao Metro Line No. 2 (China) was studied in this paper, adopting the staged blowing mode, and dust removal fans and dry dust removal boxes were installed in the working area. The working environment is directly associated with safety, efficiency,
and quality of the tunnel construction, as well as workers’ physical and mental health conditions[13]. A large amount of dust is generally generated during the tunneling process, which can greatly affect the workers’ working conditions in the tunnel[14]. The basic principle of tunnel ventilation is the dilution of vehicle emissions by providing fresh air and then removing the exhaust air from the tunnel[15-16]. The exhaust air can be removed via a portal (a location where the tunnel carriageway opens up to the surrounding environment), via a ventilation outlet (e.g., a stack), or via a combination of both[17-18]. The rock-dust moves with the airflow, and the layout of the ventilation system directly affects the rock-dust distribution and quality of air in construction of a TBM-based tunnel[19-20].

The construction of a TBM-based tunnel has been globally studied by numerous scholars. Zhang et al. used the computational fluid dynamics (CFD) to numerically simulate the ventilation process of the tunnel construction under different tunneling velocities. The distribution properties of the airflow and the dust were analyzed as well. The reliability and stability of the ventilation scheme for construction of a TBM-based tunnel were accordingly improved[21].

Xia et al. studied the optimal ventilation distance of the main blowing vent in the working area of a tunnel by studying the ventilation situation from the main ventilation position to the working face[22].

Wang et al. conducted a numerical study on the rock-dust movement and rock-dust distribution in a hybrid ventilation system to be used during construction of a TBM-based tunnel. The movement and distribution properties of the rock-dust particles in the tunnel were obtained. It was concluded that the ventilation dust-removal effect of the far-pressing-near-absorption (FPNA) ventilation dust-removal system was superior to that of the other systems under certain conditions[23].

Hargreaves et al. performed a numerical study on the ventilation environment in construction of a TBM-based tunnel using a theory related to the heat transfer coefficient. The expression of a continuous function between the length of the pipeline and the temperature inside the pipeline was derived. A computer-based program that can compute the ventilation and the heat dissipation during the construction of a tunnel by TBM was compiled as well[24].

Toraño and Torno utilized the combination of numerical simulations and field measurements to determine the movement properties of the wind field and the airflow-dust coupled field at the working face[25].

At present, compared with study of rock-dust control technology, several researches were conducted on the diffusion properties of the airflow and dust, and loss of the heat transfer in construction of a TBM-based tunnel. At the same time, the models simulated by the existing numerical methods have been notably simplified, while the simulation results were not consistent with the actual situation in partial areas with certain errors. Therefore, by using the numerical simulations and field measurements, a more realistic physical model for construction of a TBM-based tunnel was created in this paper. In addition, a mathematical model that can appropriately reflect the movement properties of the airflow and rock-dust was adopted. The rock-dust distributions in the tunnel under different heights of the exhaust vents and various blowing distances were studied as well. The movement and distribution properties of the airflow and rock-dust were obtained. Besides, the level of particulate pollution in the working area was reduced.

2. Physical and mathematical models

2.1. Physical model
The diameter of TBM-based tunnel of Qingdao Metro Line No. 2 (China) was 6.3 m, and the total length was 11.5 km. In this research, the driving construction tunnel of the project was taken as the research objective, and the overall equipment model was established and simplified. The total length of the model was 135 m. The model was composed of seven main parts as follows: cutterhead, host shield, supporting robot arm, trolley, ventilation duct, blowing (exhaust) fan, and dust removal box. The primary blowing vent was located at the top of the trolley that was about 110 m away from the heading, and the diameter of the duct was 1200 mm. The secondary blowing fan was about 5 m ahead, with the duct diameter of 600 mm. The secondary blowing vent was located at the right side of the
tunnel, which was within 40 m away from the heading. The exhaust vents were located below the carrier, one on each side. The distance between the crushed-rock conveyor and the heading was 16 m. According to the actual ventilation design on-site, the primary blowing air volume in the tunnel was 20 m$^3$/s, and the secondary blowing and exhaust air volumes were both equal to 8 m$^3$/s.

ICEM_CFD pre-processing software built-in ANSYS was used to mesh the physical model to obtain high-quality mesh parameters, which ensured the accurate identification of the grids by FLUENT ANSYS software and improved the accuracy of simulation as well[26]. The grid adaption and adjustment were implemented only in the flow area that needed to be refined, which could better represent a grid model for construction of a TBM-based tunnel of Qingdao Metro Line No. 2, and save the time required for computation. The meshing result is shown in Fig. 1, in which the total number of grids was 118973.

![Fig. 1 Mesh generation on the established model of the tunnel and Arrangement of measuring points.](image)

### 2.2. Mathematical model

In the construction of a TBM-based tunnel, fresh air passed through the tunnel working area at the top of the tunnel, and the rock-dust generated in the tunnel was sucked into the dust removal fan[27]. Due to the complicated flow process of rock-dust through the supported working area and the air duct, in this study, the fluid dynamics was employed to develop the flow-related characteristic mathematical models, including three-dimensional (3D) steady-state airflow model and the rock-dust flow model[28-29]. In addition, three hypotheses are proposed as follows:

1. The ventilation air was modeled as a 3D, viscous, and incompressible Newtonian fluid.
2. The airflow was also treated as a steady hydrodynamical turbulence.
3. The duct leakage was ignored, and the duct flow and pressure losses were not taken into account[22].

Although the trajectory of the dust particles in construction of TBM-based tunnel was solved using the Lagrangian method, only the resistance and gravity were considered, whereas the other forces were neglected due to the small magnitude[30]. The equilibrium equation of the particle phase is given by

$$\frac{du_p}{dt} = 0.75 \frac{C_D \rho u_p - u}{\rho_p d_p} (u - u_p) + \frac{g_s (\rho_p - \rho)}{\rho_p}$$

(1)

Where $u_p$ is the velocity of dust particle, m/s;
$t$ denotes the time required for particle movement, s;
$g_s$ is the acceleration of gravity, m/s$^2$;
$u$ represents the airflow velocity, m/s;
$ho_p$ is the dust density, kg/m$^3$;
$ho$ denotes the gas density, kg/m$^3$;
$C_D$ is the drag coefficient;
\[ d_p \] denotes the diameter of the dust particle, m.

The particle trajectory control equation is given by

\[
\frac{du_p}{dt} = \frac{1}{\tau_p} (u - u_p)
\]  

(2)

where, \( \tau_p \) is the relaxation time of the dust particle, s.

Considering the influence of turbulence on the randomness of the particle, the instantaneous velocity \( u \) of the airflow can be regarded as the sum of the average amount \( u \) and the pulsation amount \( u'(t) \), i.e.

\[ u = u + u'(t) \]  

(3)

For the k-\( \epsilon \) model, the integral time length of the particle is approximated as the Lagrangian integration time length \( T_L \) of the airflow, i.e.

\[ T_L = 0.15 \frac{k}{\epsilon} \]  

(4)

where \( k \) is the turbulence pulsation kinetic-energy, J;

\( \epsilon \) denotes the dissipation rate of the turbulence pulsation kinetic-energy, \( \% \).

When the particles interact with the discrete vortices of the fluid, it is assumed that the fluid pulsation velocity \( u' \) in the turbulent vortex satisfies the Gaussian probability density distribution, i.e.

\[ u' = \xi \sqrt{(u')^2} \]  

(5)

where \( \xi \) denotes a random number obeying a normal distribution;

\[ \sqrt{(u')^2} \] is the root mean square of the pulsation velocity at that point, m/s[31-32].

For the k-\( \epsilon \) model, assume that the turbulence of each point is isotropic, then

\[ \sqrt{(u')^2} = \sqrt{(v')^2} = \sqrt{(w')^2} = \sqrt{\frac{2k}{3}} \]  

(6)

Where \( u', v', \) and \( w' \) are the fluid pulsation velocities in three directions, m/s[33].

### 2.3. Model Validation

As shown in Figure 1, 42 measuring points are selected from the range of TBM construction tunnel personnel's action to collect data. Combined with the data of the same position derived from the numerical simulation results, the relative error between the two points is obtained to verify the model.

Table. 1 Validation data for the validity of simulation results

| Measuring conditions | Data type | \( H_e = 1.8 \) m | \( L_P = 35 \) m |
|----------------------|-----------|-----------------|-----------------|
| **Point number**     | **Dust concentration (mg/m³)** | **Air velocity (m/s)** |
| Point number         | Simulation value | Measured value | Simulation value | Measured value |
| 1                    | 37.38      | 39.93           | 3.15            | 2.85           |
| 2                    | 21.55      | 19.68           | 4.6             | 4.86           |
| 3                    | 24.12      | 29.04           | 6.37            | 7.01           |
| 4                    | 11.73      | 8.65            | 5.83            | 5.16           |
| 5                    | 7.48       | 5.39            | 2.61            | 2.15           |
| 6                    | 6.69       | 7.64            | 2.02            | 1.48           |
| 7                    | 5.3        | 5.42            | 1.16            | 1.36           |
The relevant data is shown in Table 1. The error of dust concentration is 14.58%, and the error of Air velocity is 13.27%, The mean error is 13.93%, proving that the simulation results in this study have a high accuracy, and can reflect the actual field measurement.

3. Numerical simulation of different heights of exhaust vent

The height of the dusty return airflow was associated with the equipment arrangement in the host and the tail shield. For the same TBM, the equipment arrangement would not change during a single tunneling process. The dust-removal effect of the exhaust vents could be affected by the relative positions of the exhaust vents and the dusty return airflow. At the same time, the airflow distribution in the working area was affected by the distribution of the exhaust negative-pressure itself. The simulation was carried out by changing the relative heights of the exhaust vents. The heights from the sidewalks ($H_E$) of 0.3, 0.6, 0.9, 1.2, 1.5, 1.8 (initial value), and 2.1 m were selected for doing research and analysis. The relationships between the airflow distribution in the working area and the rock-dust distribution in the tunnel and the height of the exhaust vents were discussed.

As shown in Figure 1, there are 21 nodes in the sidewalks on the left and right sides of the tunnel, 42 nodes in total. From the simulation results, the rock dust concentration data at these 42 nodes are derived, and the network diagram is drawn.

Figure 2 shows the numerical simulation results of wind flow and rock dust distribution in the tunnel, as well as the network diagram of rock dust concentration at different positions in the tunnel.

### Table 1

| Height (m) | Error (%) | Mean Error (%) |
|------------|-----------|----------------|
| 8          | 4.77      | 14.58          |
| 9          | 4.15      | 13.27          |
| 10         | 3.52      | 1.07           |

(1) $H_E = 0.3$ m

(2) $H_E = 0.6$ m
(3) \(H_E = 0.9\) m

(4) \(H_E = 1.2\) m

(5) \(H_E = 1.5\) m

(6) \(H_E = 1.8\) m
As displayed in Fig. 2, the findings can be presented as follows:

1) The fresh airflow enters the tunnel through the primary blowing. A part of the airflow is compressed by the secondary blowing fan, and the other airflow continues to move forward along the tunnel. When moving nearby the secondary fan, the backflows occur on both sides of the trolley due to the wall attachment effect. The secondary blowing airflow enters the working area and passes through the front area, and the backflow occurs at a distance from the heading (L) of about 10~11 m. A part of the airflow is absorbed by the exhaust vent, and the rest of the airflow continues to move backward along the tunnel. During the tunneling process by a TBM, as the rock slags slide from the mud tank to the belt conveyor and sent to the carrier, a large amount of rock-dust particles is generated when the cutterhead cuts the hard rock. These rock-dust particles are coupled with the secondary blowing airflow and spread backward together.

2) The height of the dusty return airflow is about 1.3~1.9 m away from the lowest point of the tunnel, which is within 0.5~1.1 m above the sidewalks. The return airflow mainly spreads backwards along the inside of the trolley. The airflow velocity and trajectory distribution in the working area are relatively uniform. As the return airflow gradually moves backward, the trajectories start to radiate and diffuse around. Simultaneously, due to the ejection effect of the blowing vent, at the range of 26~40 m from the heading, the return airflow begins to deflect toward the upper part of the tunnel, and the dust begins to spread from the bottom of the tunnel to the cross-section of entire tunnel. At the range of 40~60 m, due to the forward compression of the primary blowing airflow, it is coupled with the return airflow to form a low-velocity coupled air-curtain, which is interfered with the backward diffusion of the return airflow. Therefore, a certain degree of rock-dust accumulation occurs in this area. As illustrated in the network graph, the areas with the rock-dust concentration of higher than 2 mg/m$^3$ are roughly the measurement points Nos. 1~9, that is, within the space of 58.37 m from the heading, the measurement points Nos. 2~7 (about 16 m ~ 52m away from the heading) are included in the main activity area of the workers. Simultaneously, the dust concentration in measurement points Nos. 5~7 is relatively lower than that of the other areas due to the dust-removal effect of the exhaust vents.

3) The influence of changing the height of the exhaust vents on the rock-dust distribution in the tunnel is mainly reflected in the distribution of rock-dust concentration in the working area. Since the average airflow velocity in the working area is about 1.85~3.43 m/s, the exhaust vents cannot exhaust all the dusty airflow, and the rock-dust inevitably spreads into the rear of the tunnel. In the coupled wind field, the velocity of the dusty airflow is decreased to about 0.17~0.68 m/s. The rock-dust is
blocked on one side of the wind field, and cannot further diffuse backward. The overall dust-removal effect in the working area is reflected in the average rock-dust concentration. When $H_E = 0.6$ m, the rock-dust concentration in the working area is the minimum, and the best dust-control effect is obtained.

(4) The A, B, C, D, and E cross-sections are the tunnel cross-sections at distances of 15, 20, 25, 30, and 35 m away from the heading. The average rock-dust concentrations of the cross-sections at different heights of the exhaust vents are shown in Table X. It shows that the average rock-dust concentration of the cross-section in this area is initially increased and then decreased with the increase of the distance, and a maximum value is obtained between the B and C cross-sections. The rock-dust concentration in the lower part of the cross-section is generally high, i.e., the rock-dust in the working area mainly moves along the lower part of the tunnel. In the C, D, and E cross-sections, the rock-dust concentration begins to increase near the jet zone of the secondary blowing airflow, indicating that under ejection effect of the secondary blowing airflow, the rock-dust diffuses with the return airflow along the lower part of the tunnel and re-enters the 15~35 m area with more workers, making the rock-dust concentration to be generally higher than the allowable concentration.

The network graph shows the values of rock-dust concentration at the height of breathing zones of the sidewalks on both sides of the tunnel. It can be seen that there is almost no rock-dust distribution in the tunnel behind the measurement point No. 11. The higher rock-dust concentrations appear in two spaces of the measurement points Nos. 1~3 and 7~11. The highest rock-dust concentration is generally obtained at the measurement points Nos. 7~11, where the dusty airflow velocity is decreased, the coupling effect between the airflow and the rock-dust is weakened, and the ejection effect of the secondary blowing airflow is reduced. In addition, affected by the coupled wind field, the rock-dust cannot continue to diffuse backward and then accumulates in this area.

4. Numerical simulation for different positions of secondary blowing vent

Without changing the blowing air volume, the change of the position of the blowing vent would change the airflow velocity and distribution in the working area. If the airflow velocity was very high, the ventilation efficiency of the exhaust vents would be reduced, however, if it was very low, the coupling performance of the rock-dust and the airflow would be weakened. Both situations would have an adverse effect on the exhaust dust-removal. At the same time, as the blowing vent moved backward, the strength of the coupled wind field in the middle of the tunnel would change, and the airflow trajectory in the working area would also significantly change, which had an unknown impact on the dust-control work in the entire tunnel space.

Next, the simulation was carried out by changing the distance between the blowing vent to the heading ($L_P$). Let $H_E = 0.6$ m; the distances from the heading of 25, 30, 35, 40, 45, 50, 55, and 60 m were selected for conducting research and analysis. The variation properties of the airflow distribution in the working area and the rock-dust distribution in the tunnel with the positions of the blowing vent were discussed.

(1) $L_P = 25$ m
(2) \( L_P = 30 \) m

(3) \( L_P = 35 \) m

(4) \( L_P = 40 \) m

(5) \( L_P = 45 \) m
Fig. 3 Result of simulation about air streamlines and dust concentration distribution indicating the positions of secondary blowing vent

As shown in Figure 1, there are 21 nodes in the sidewalks on the left and right sides of the tunnel, 42 nodes in total. From the simulation results, the rock dust concentration data at these 42 nodes are derived, and the network diagram is drawn. Figure 3 shows the simulation results under this group of parameters and the rock dust concentration at each measuring point. As displayed in Fig. 3, the findings can be presented as follows:
(1) When LP is increased from 25 to 60 m, as the distance between the secondary and the primary blowing airflows is shortened, the radical diffusion range of the secondary blowing airflow trajectory is gradually increased, and the backflow air volume caused by the secondary blowing airflow is gradually reduced. When 25 m \( \leq L_P \leq 30 \) m, the radial cross-section of the airflow cannot be fully expanded, while the blowing airflow enters the front of the working area. Simultaneously, when the airflow velocity is higher than 3 m/s, the effect of the exhaust vents on the dusty return airflow is negligible, resulting in a large amount of the return airflow diffuses backward. When 30 m \( \leq L_P \leq 55 \) m, as the secondary blowing distance continues to increase, the velocity of the airflow entering the front of the working area is gradually reduced from 2.94 m/s (when \( L_P = 30 \) m) to 0.97 m/s, and the influence of the exhaust vents on the return airflow is continuously enhanced. At the same time, with the increase of blowing distance, the blowing airflow trajectory continuously diffuses in the radial direction, resulting in an increase in the cross-section of the airflow entering the working area. Therefore, the dust-control air-curtain is gradually formed at \( L = 15~20 \) m. When \( L_P > 50 \) m, the return airflow is affected by the secondary blowing airflow in the right lower part of the tunnel at \( L = 20~35 \) m beforehand, causing an airflow disorder in this area. Therefore, in the middle section of the tunnel, a primary blowing airflow cannot form a coupled field with the return airflow. Simultaneously, with the increase of \( L_P \), the average airflow velocity in the working area is reduced from 3.174 m/s at \( L_P = 25 \) m to 0.357 m/s at \( L_P = 60 \) m, and the return airflow velocity is attenuated from 2.924 m/s at \( L_P = 25 \) m to 0.493 m/s at \( L_P = 60 \) m. When 55 m \( \leq L_P \leq 60 \) m, the velocity of the secondary blowing airflow is low (about 0.37–0.53 m/s) at \( L = 14~23 \) m. When the airflow approaches the carrier, it tends to be stabilized, and a dust-control air-curtain with a low-velocity airflow is formed between the working and the non-working areas.

(2) Carried by the airflow, the dust generated by the cutterhead mainly goes into two directions: one is exhausted by the exhaust vents, and the other is carried to the rear of the tunnel by the airflow flowing backwards alongside of the exhaust duct. When 25 m \( < L_P < 30 \) m, in front of the secondary blowing vent, the return airflow of the left and right sides of the tunnel is subjected to the ejection of the secondary blowing airflow. As a result, the velocity direction of the airflow is twisted, and the airflow re-enters into the working area to form two vortex fields. The rock-dust close to \( L = 42.82 \) m is forwarded to the working area by the ejection effect. Therefore, most of the rock-dust cannot be diffused with the return airflow to the rear of the tunnel. At this time, \( L_D = 58.37 \) m, \( C_D = 14.56 \) mg/m³, and the rock-dust concentration in the tunnel at \( L > 52 \) m is lower than 10 mg/m³. When 30 m \( < L_P < 55 \) m, the airflow velocity in the low-velocity zone between the primary and the secondary blowing vents is gradually increased. The return airflow is coupled with the primary blowing airflow to form a coupled air-curtain behind the secondary blowing vent, preventing the rock-dust from spreading backwards. After the secondary blowing airflow enters the working area, the return-flow occurs at \( L = 10~12 \) m. Simultaneously, the rock-dust is carried by the airflow, a part of which is exhausted by the exhaust vents, and the other part is diffused backward with the return airflow. As the ventilation distance of the secondary blowing airflow increases, the velocity of the return airflow gradually decreases, and the air volume treated by the exhaust vents increases as well. Therefore, the rock-dust concentration decreases from 11.05 mg/m³ at \( L_P = 30 \) m to 2.18 mg/m³ at \( L_P = 55 \) m, while \( L_D \) reduces from 72.26 m to 18.83 m, meanwhile the dust with a concentration of 2.156 mg/m³ gather near \( L = 67.24 \) m in the tunnel. When \( L_P = 60 \) m, the blowing airflow is sucked into the exhaust vents, while moving to \( L = 13.42~16.35 \) m by the negative pressure near the exhaust vents. A dust-control air-curtain is formed, and the rock-dust generated in the tunnel is controlled at the range of \( L = 12.96~15.95 \) m. There is basically no rock-dust distribution at the rear of the tunnel when \( L > 16.4 \) m, and the optimal dust-control effect is achieved.

(3) The A, B, C, D and E cross-sections are the tunnel cross-sections at distances of 15, 20, 25, 30, and 35 m from the heading. The average rock-dust concentrations of the cross-sections at different positions of the secondary blowing vent are shown in Table X. As shown in Table X, when \( L_P < 50 \) m, the average rock-dust concentration of the cross-section in this area is initially increased and then decreased with the increase of \( L_P \). When \( L_P > 50 \) m, the average rock-dust concentration is decreased...
with the increase of the distance from the cross-section to the heading. It can be considered that the dusty return airflow cannot return to the working area through the ejection of the secondary blowing airflow when \( L_P > 50 \text{m} \). At this time, the rock-dust is diffused by the host, coupled with the secondary blowing airflow, and captured by the exhaust vents. Since the height of return airflow is almost the same as that of the exhaust vents and is relatively low, the dusty airflow is mostly exhausted by the exhaust vents, and only a small amount of the rock-dust escapes from the negative pressure of the exhaust vents and diffuses backward. However, at this time, the rock-dust is generally confined in the frame of the trolley, and the concentration is lower than 3.68 mg/m\(^3\). In addition, the rock-dust concentration near the sidewalks is basically less than 2 mg/m\(^3\).

(4) The network graph shows the values of rock-dust concentration at the height of breathing zones of the sidewalks on both sides of the tunnel. It shows that the rock-dust particles can only spread with the return airflow of the secondary blowing airflow to the measurement point No. 11 as well. When \( L_P > 55 \text{m} \), the areas nearby the sidewalks are basically not affected by the rock-dust. When \( L_P = 55 \text{m} \), only the rock-dust concentration near the measurement points Nos. 1-6 is higher than 2 mg/m\(^3\), and when \( L_P = 60 \text{m} \), the rock-dust concentration only nearby the measurement points Nos. 1~4 is higher than 2 mg/m\(^3\). Therefore, it is considered that \( L_P = 60 \text{m} \) is the optimal secondary blowing distance for the dust-control effect.

![Fig. 4 Relations between diffusion distance and concentration of dust when using different LP](image)

The function represented by the image in the green box has a high degree of fitting, and the formula form is simple, while when LP of other formulas is large, there is great difference between curve and data results. The mathematical relationship between the rock-dust diffusion distance and the secondary blowing distance (\( L_P \)) computed by MATLAB software is given by

\[
L_D = 69.3\sin(0.058L_P - 0.6)+13.23\sin(0.335L_P - 7.9)
\]

5. Field measurements and verification of the results

In order to verify the results of simulation, it is necessary to measure the initial ventilation design in the construction of a TBM-based tunnel of Qingdao Metro Line No. 2, and the airflow velocity and rock-dust concentration at each measurement point in the tunnel with \( H_E = 0.6 \text{m} \) and \( L_P = 60 \text{m} \). The measurement points were set as follows: the measurement point No. 1 was set at the tail shield with a distance of 10 m from the tunnel. The other measurement points were set on both sides of the sidewalks \((Y = \pm 1.5 \text{m})\) along the height of 1.5 m above the sidewalks of the trolley with an interval of
6 m. There are totally 42 measurement points from the tail shield to the end of the equipment area, as shown in Fig. 1. According to the numerical simulation results, the rock dust in the tunnel mainly exists before measuring point 8. Therefore, in order to reduce the amount of data and improve the efficiency, measuring point 1-8 is selected for field measurement and research. The actual airflow velocity and rock-dust data were measured on-site by using the measurement equipment, as shown in Fig. 5. According to the positions shown in Fig. 1, the data of each measurement point were measured in real-time during the field measurement, and the measured values were compared with the simulated values.

![Fig. 5 Photograph of Field measurement and measuring equipments](image)

Table. 2 shows the relationship of the variation trend and the magnitude between the measured and simulated data. As illustrated in Table. 2, the results of simulation are almost consistent with the field measurements. The variation trends of airflow velocity with L are similar. According to the calculations, the average relative error of airflow velocity is 12.1%, and 17.3% of Dust concentration. When the height of the exhaust vents is consistent with the height of the dusty return airflow (H_E = 0.6 m) and the secondary blowing distance is 60 m, the simulation results are basically consistent with the field measurement results, which proves that the ventilation condition can effectively control the rock dust in the construction of TBM tunnel.

| Measuring conditions | H_E = 0.6 m | L_P = 60 m |
|----------------------|------------|------------|
| **Datatype** | Dust concentration (mg/m³) | Air velocity (m/s) |
| **Point number** | Simulation value | Measured value | Simulation value | Measured value |
| 1 | 14.46 | 12.87 | 1.04 | 1.21 |
| 2 | 10.40 | 9.36 | 1.18 | 1.27 |
| 3 | 5.07 | 6.84 | 1.69 | 1.56 |
| 4 | 2.22 | 1.73 | 2.05 | 2.38 |
| 5 | 1.69 | 1.42 | 2.43 | 2.74 |
6. Conclusions

(1) In the construction of a TBM-based tunnel, the primary and secondary blowing airflows could form a coupled air-curtain at distances of 55~75 m away from the heading, disappearing when \( L_P > 50 \) m. The coupled wind field could prevent the rock-dust regarding further diffusing to the rear of the tunnel.

(2) The simulation results for the secondary blowing distance showed that as the distance increased from 25 to 60 m, the rock-dust was easier controlled by the longer secondary blowing distance due to the decrease of the airflow kinetic energy and the return air volume. The dust concentration was reduced from 10.36 mg/m\(^3\) at \( L_P = 25 \) m to 1.30 mg/m\(^3\) at \( L_P = 60 \) m. In addition, when \( L_P > 50 \) m, the dust-control air-curtain was gradually formed near the carrier. The dust diffusion distance was controlled within the range of \( L < 17 \) m at \( L_P > 55 \) m.

(3) By changing the height of the exhaust vents in the working area, the effect of dust control on the ventilation system could be effectively improved. When the position of the exhaust vents is close to the height of the dusty return airflow, it is more beneficial to improve the dust removal effect. In this study, when the height of the exhaust vents is 0.6 m away from the sidewalks, the rock-dust concentration in the tunnel is low, and the dust concentration is reduced to below 5.29 mg/m\(^3\). In addition, the variation property of the concentration with the height of the exhaust vents could be fitted to the Eq. (7), reflecting the correlation to a certain extent.

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