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EFFECTIVENESS OF DRILLING VENTILATION ON HEADING FACE IN LONG-DISTANCE TUNNELING

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Abstract

This paper explores the effectiveness of drilling ventilation in a semi-enclosed mine during the long-distance tunneling. Firstly, a resistance-pressure energy balance equation was established. Then, the drilling ventilation effect was analyzed at different borehole lengths and borehole diameters. After that, the drilling conditions were determined for the effective drilling ventilation of long-distance tunneling. The relationships between borehole diameter, borehole length, borehole position and effective airflow on the heading face were discussed in details. The results show that the effective airflow increases with the borehole length and the borehole diameter. However, the increase ceases when the airflow reaches the saturation point. Beyond this point, the maximum airflow depends on the fan capacity. The ventilation effect can be improved by increasing the borehole length between 0~200m. When the length falls between 100~650m, the ventilation effect can be enhanced by expanding the borehole diameter. When the auxiliary fan had a power of 2×30kW and the borehole diameter was 665mm, the transfer distance fell between 50~250m and the effective airflow was enough to prevent the circulation of foul air. The research findings shed important new light on downhole air management.

Key words: drilling ventilation, effectiveness analysis, heading face, long-distance tunneling

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1. Introduction

The adequate supply of required airflow is an important issue in the long-distance heading face of underground coal mine (Kuyucak, 1998; Li et al., 2010; Suvar et al., 2017; Wu et al., 2017). Roadway tunneling system likes a semi-closed pipe network (Tuck, 1997), during the roadway development, in which toxic, harmful substances coexist with inflammables, explosives and heat radiation (Hartman et al., 2012; Marino et al., 2018). These hazard factors increase the risk of mining accidents (Nural, 1998). For a long time, heading face accident is the most during coal mine production. While differing with locale and mission of outer space, human miners are no less depending on an artificial atmosphere to sustain them in underground mines (Morar et al., 2017; Semin and Levin, 2019). Once an accident occurs, it often causes great casualties and property damage. However, traditional single heading face ventilation, in which the air enters the workplace from only one end of the roadway, encounters many problems in the tunneling process, such as long route, high resistance and frequent leakage (Tu and Lv, 2003). Various technologies have been developed wildly and applied to supply required airflow in the long-distance heading face (Niu et al., 2011). Shortening ventilation route is the key to solve the problem.

Drilling ventilation is an effective method to improve working environment and to ensure workers safety, and it has been developed to alleviate the ventilation pressure of long-distance tunneling (Wang and Qiao, 2012). Unlike the single heading face

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ventilation, it is a technique of using large-diameter vertical boreholes to ventilate (Li, 2012). Required airflow which applied by an auxiliary fan is pushed into the heading face through vertical drilling from a certain level where on the ground or in the middle of the tunnel (Zhao et al., 2014). Polluted air also can be exhausted through boreholes (Lei, 1989; Zhai et al., 2011).

Drilling ventilation had been studied and applied wildly in China. Lin et al. (1987); Zhang and Lin (2008) proposed to drill boreholes in the middle section or the surface to improve ventilation in long-distance tunneling. Teng (2011) expounded the principles of drilling ventilation and construction technology. Yang and Meng (2014) proposed to combine ventilation theory of using borehole with transfer airflow storeroom, literature proposed to combine ventilation theory of using borehole with transfer airflow storeroom, and compared the integrated ventilation method with single fan and single heading face. These studies shown that the drilling ventilation could achievs a good effect of ventilation and management facilitate, but the construction cost would be too much. In addition, the engineering application of drilling ventilation is not mature enough yet. This technology lacks necessary theoretical supporting and facing several bottlenecks, such as where to provide ventilation power, and how to determine the length and diameter of ventilation holes etc.

This paper probes into the effect of drilling ventilation in long-distance tunneling. Firstly, a resistance-pressure energy balance equation was established. Then, the auxiliary fan operating point were determined for the effective of long-distance drilling tunneling. After that, the drilling ventilation effect was analyzed with different.

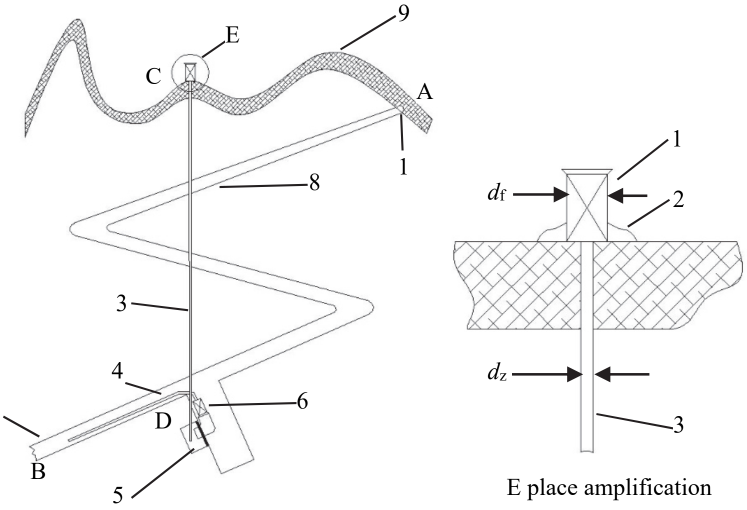
2. Material and methods

This article takes the $1^{\#}$ ramp of mine as the research object. The ventilation system is shown in Fig. 1, where the segment A-B (single-head ventilation) is 2,400m long, and the segment C-D-B (drilling ventilation) is 1,091.36m. The borehole diameter is (d_{z0}) 301mm, the diameter of the flexible air duct (d_{r0})is 600mm, and the power of transfer fan is 2×11kW. Compared with single-end ventilation, drilling ventilation has shorter ventilation distance (Gao and Zhao, 2012). A large-diameter ordinary steel pipe, that is a casing, is installed in the borehole. The casing is equivalent to an air cylinder. Auxiliary fan is installed at the ventilation level of borehole. A steel elbow which leading to working surface is welded on the drilling casing in the construction roadway. The steel elbow is connected to the boring head by upper air duct. Borehole is carried out from the ventilation level above the construction roadway in most casings, and the construction is completed before the roadway is connected (including casing installation and cementing). The airflow is transferred from the transfer wind store room by the auxiliary fan, and then blown into the heading face by the transfer fan.

Borehole should be carried out from the construction roadway to the lower ventilation level if it subjected by objective conditions. Drilling ventilation mode that below the construction roadway doesn't usage normally. There are many disadvantages of this method. First, the amount construction cost is increased. Second, it affects the construction of the roadway due to the parallel construction of the borehole construction and the roadway construction. The third one is that the borehole is located in a poor ventilation environment. The last point is that the partial pressure loss is largely. Too many elbows are installed, which affect the ventilation effect.

The construction process of the ventilation drilling involves some steps as follow:

(1) Measuring drilling parameters. There are two tasks of this work: one is to find the location of the borehole, the other one is to measure the elevation of the borehole.



E place amplification

Fig. 1. The ventilation system in a metal mine
(Note: 1-Auxiliary fan; 2-Concrete seal; 3-Air shaft; 4-Flexible air duct; 5-Transfer wind library; 6-Transfer fan; 7-Heading face; 8-Ramp; 9-Surface; 10-Ramp inlet; d_f- Diameter of fan; *dz*-Diameter of air shaft)

(2) Drilling the borehole (Fig. 2a.).

(3) *Equipping the iron air duct* (Fig. 2b.). The iron air duct can be equipped after the drilling acceptance completly. In this process, the welding must be meeting the requirements, the nut is tightened, and the crane operation meets the requirements.

(4) *Pouring concrete* (Fig. 2c and Fig. 2d). The consistency and depth of the mud are strictly controlled during the excavation. The concrete should be continuously poured to ensure the strength. The air duct cannot be pulled out when pouring concrete. Once pulled out, the steel pipe is broken and it is much troublesome to handle.

When the rock formation is broken or soft rock existence during the drilling process, there will be problems such as difficulty in discharging powder, collapse of the hole wall, reduction of diameter, and influence of porosity. Combined with the on-site situation, there are two main improvement methods of the production process: (1) ZDY-4000S full hydraulic drilling rig can be used. The rig features high power, atmospheric pressure and low air pressure. High-strength geologic auger drills are required during using. (2) Dynamic pressure conveying using a large flow high pressure mud pump.

3. Results and discussion

3.1. Auxiliary fan operating point

The main fan operating point (R_{QQf}, Q_f) can be obtained by the requiring flow rate of the heading face and the wind resistance of the air dusts. For the auxiliary fan, the characteristic curve is given hardly. Therefore, the actual operating condition of the main fan (R_{QQf}, Q_f) usually does not match the calculated one.

In order to predict the actual working conditions of auxiliary fan, the flow rate Q_f and the wind pressure h_f can be obtained according to the designed parameters of the fan and the two operating points (($h_{\max}$, $Q_{\min}$) and ($h_{\min}$, $Q_{\max}$)) (Li, 2006). Here, $h_{\max}$ ($h_{\min}$) is the maximum (minimum) wind pressures of the fan (Pa), while $Q_{\max}$ ($Q_{\min}$) is the maximum (minimum) flow rates of the fan (m^3/s). Then, the operation parameters of the fan can be approximated by changing the relationship between Q_f and h_f (Lu and Yang, 2011). Wind pressure h_f is a quadratic function of flow rate Q_f and proportional to wind resistance R (Li et al., 2010; Wang and Qiao, 2012). The resistance characteristic curve is about the quadratic function h_r of Q_f (Huang, 1986), thus, the resistance-pressure energy balance can be established as Eq. (1):

$$\begin{cases} h_{\mathrm{f}} = \dfrac{Q_{\mathrm{f}} - Q_{\max}}{Q_{\min} - Q_{\max}} h_{\max} + \dfrac{Q_{\mathrm{f}} - Q_{\min}}{Q_{\max} - Q_{\min}} h_{\min} \\ h_{\mathrm{r}} = RQ_{\mathrm{f}}Q = \dfrac{RQ_{\mathrm{f}}^{2}}{p_{\mathrm{i}}} \end{cases} \tag{1}$$

where: $Q_f \in (Q_{\min}, Q_{\max})$. p_{i} is the leakage reserve coefficient of the flexible air duct; If the fan operates steadily, then h_f is equal to h_r. In this case, the flow rate Q_f is the actual working flow of the fan.

The outlet flow of the flexible air duct Q is equivalent to the effective airflow reaching the heading face:

$$\begin{cases} Q_{\mathrm{f}} = \dfrac{(m+\sqrt{n})p_{\mathrm{i}}}{2R} \\ Q = \dfrac{Q_{\mathrm{f}}}{p_{\mathrm{i}}} \end{cases} \Leftrightarrow \begin{cases} Q_{\mathrm{f}} = \dfrac{50(m+\sqrt{n'})p_{\mathrm{i}}}{R_{100} \cdot L} \\ Q = \dfrac{Q_{\mathrm{f}}}{p_{\mathrm{i}}} \end{cases} \tag{2}$$

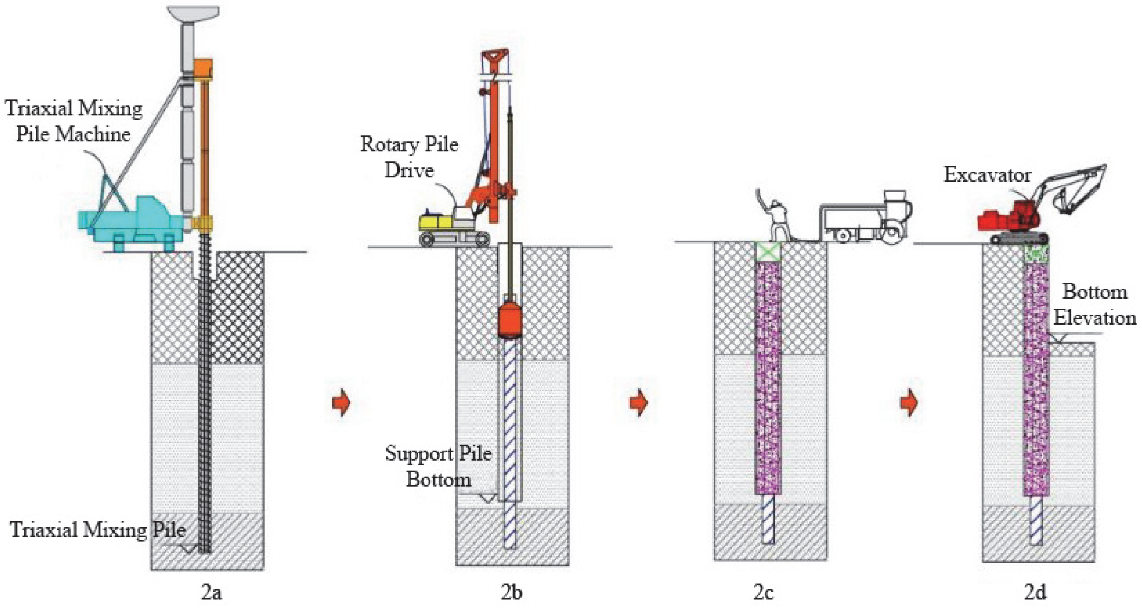


Fig. 2. Construction process of the borehole
(Note: 2a-Drilling forming; 2b-equipment air dust; 2c-Pouring concrete; 2d-Drilling forming**)**

where:

$$\begin{cases} m = \dfrac{h_{\max} - h_{\min}}{Q_{\min} - Q_{\max}} \\ n = m^2 + 4\dfrac{R}{p_{\mathrm{i}}}\dfrac{h_{\min}Q_{\min} - h_{\max}Q_{\max}}{Q_{\min} - Q_{\max}} \\ n' = m^2 + \dfrac{R_{100} \cdot L}{25p_{\mathrm{i}}}\dfrac{h_{\min}Q_{\min} - h_{\max}Q_{\max}}{Q_{\min} - Q_{\max}} \end{cases} \tag{3}$$

L is the length of the flexible air duct (m). The other parameters are the same as above.

In $1^{\#}$ ramp as shown in Fig.1, the air shaft length (L_{z0}) is 233.36m and the diameter (d_{z0}) is 301mm for drilling ventilation. The auxiliary fan has a power of 2×11kW, a rated flow of 180~450m^3/s, and a rated pressure of 4,800~5,000Pa. The leakage reserve coefficient p_i of the borehole is 2.07. According to the above equation, the outlet flow of the borehole was estimated as 0.9954m^3/s, which is close to the actual flow of 0.7118m^3/s (although the fan does not operate in the stable range). Thus, it is feasible to determine approximately the required airflow conditions by Eq. (2).

3.2. Resistance of borehole and transfer fan

Ventilation drilling adopts the seamless welding metal pipe to insert vertically into the tunnel, regardless of wind resistance of joints and elbows, the wind resistance $R_{\mathrm{z}}(d_{\mathrm{z}}, L_{\mathrm{z}})$ of borehole would be Eq. (4):

$$R_Z\left(d_z, L_z\right) = \frac{\alpha L_z U_z}{S_z^3} + \xi_{on}\left(\frac{\rho}{2S_z^2}\right) + \xi\left(\frac{d_f^2}{d_z^2}\right)\cdot\left(\frac{\rho}{2S_f^2}\right) \tag{4}$$

The internal wall roughness degree of metal air duct merely related to its diameter (Tu and Lv, 2003). In order to analysis the relationship between diameter of drilling and ventilation effectiveness, regression analysis on the data relationships of α and the borehole diameter. The regression equation was obtained, such as Eq. (5).

$$\alpha\left(d_z\right) = 0.0062e^{-1.1941d_z}, R^2 = 0.994 \tag{5}$$

Difference between diameter of drilling fan outlet and borehole will produce local resistance, thus regression analysis on the data relationships of diameter ratio and the local resistance coefficient. The relationship can be given as Eq. (6):

$$\xi\left(\frac{d_f^2}{d_z^2}\right) = \begin{cases} 0.948\cdot\left(\dfrac{d_f^2}{d_z^2}\right)^2 - 1.9323\cdot\left(\dfrac{d_f^2}{d_z^2}\right) + 0.9818, \left(\dfrac{d_f^2}{d_z^2}\right) \in [0,1], R^2 \\ 0.13285\cdot\ln\left[10.57491\cdot\left(\dfrac{d_f^2}{d_z^2}\right)\right], \left(\dfrac{d_f^2}{d_z^2}\right) \in [0,100], R^2 \end{cases} \tag{6}$$

The bottom transfer ventilation system usually adopts flexible air duct. Wind resistance of joints and on-way were replaced by hectometer wind resistance. The transfer fan wind resistance R_{r} would be Eq. (7):

$$R_r = \frac{R_{100} \cdot L_r}{100} + \sum \xi_{bei} \cdot \left(\frac{\rho}{2s_r^2}\right) + \xi_{on} \cdot \left(\frac{\rho}{2s_r^2}\right) \tag{7}$$

where: $R_{\mathrm{z}}(d_{\mathrm{z}},L_{\mathrm{z}})$ is the wind resistance of borehole (N·S^2/m^8), d_{z} is the diameter of borehole (m), L_{z} is the length of borehole (m), α is the friction resistance coefficient of air duct (N·s/m^4), U_{z} is the perimeter of borehole (m), s_{z} is the cross-sectional area of borehole (m^2), ξ_{on} is the resistance coefficient of air duct outlet, ρ is the density of air (kg/m^3), $\xi\left(\frac{d_f^2}{d_z^2}\right)$ is the resistance coefficient of fan and borehole junction, s_f is the cross-sectional area of body of fan (m^2), R^2 is the goodness of fit, R_{r} is wind resistance of transfer fan (N·S^2/m^8), R_{100} is the hectometer wind resistance of air duct ($N{\cdot}S^2/m^8$), L_{r} is the length of flexible air duct (m), ξ_{bei} is the resistance coefficient of air duct elbow, s_{r} is the cross-sectional area of flexible air duct (m^2).

3.3. Effect of borehole length on ventilation

Borehole length is an important influencing factor of ventilation effect. Based on Eq. (2), the relationship between ventilation effect and the length of borehole can be expressed as Eq. (8):

$$Q_f = \frac{\left(-955.56 + \sqrt{913086.42 + \dfrac{4\times 7666.67\times R_z\left(d_z, L_z\right)}{p_i}}\right)\square p_i}{2R_z\left(d_z, L_z\right)} \tag{8}$$

The value of p_{i} is 1 if there is no leakage in the concrete sealing between the borehole and the auxiliary fan. The variation in required airflow with borehole length is displayed in Fig. 3.

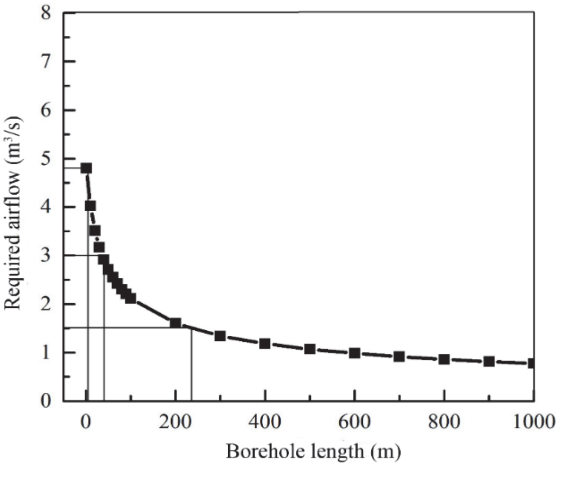


Fig. 3. Effects of borehole length on required airflow

It can be seen that the effective airflow decreased with the growth of the borehole length; the decline was particularly fast as the borehole length changed from 0mm to 200mm. The range of the borehole length should be adjusted to improve the ventilation effect. When the length of the borehole (L_{z0}) is 233.36m, the required airflow varied with the borehole diameters. The required airflow increased rapidly as the borehole diameter widened from 100m to 650m. The increase of required airflow slowed down after the diameter reached 650mm, and stabilized after the diameter surpassed 990mm.

In the target ramp, the borehole length (L_{z0}) is only 233.36m. Under this condition, the effective airflow was merely 1.5m^3/s when reached the bottom of the borehole. The real airflow is far less than the theoretical one (4.83m^3/s), failing to meet the requirement. In fact, the effective airflow is 4.8m^3/s when the borehole length (L_{z0}) is 1m, which is already close to the theoretical required airflow. Thus, the borehole is too short to enhance the ventilation effect.

3.4. Effect of borehole diameter on ventilation

When the length of the borehole remains constant, the borehole diameter becomes a major determinant of the ventilation effect. The relationship between ventilation effect and the diameter of the borehole can be obtained as given by Eq. (9).

$$Q_f = \frac{\left(-955.56 + \sqrt{913086.42 + \dfrac{4\times 7666.67\times R_z\left(d_z, L_{z0}\right)}{p_i}}\right)\square p_i}{2R_z\left(d_z, L_{z0}\right)} \tag{9}$$

It can be seen from Fig. 4 that the effective airflow increases with the diameter at a growing rate. This means the ventilation effect can be improved by increasing the borehole diameter. Since the maximum airflow of the fan is designed as 7.5m^3/s, the fan capacity has saturated when the borehole diameter increased to 990mm. Further expansion of the diameter will not promote the required airflow. Therefore, the optimal range of the borehole diameter is 100~650m. Under the said length, the required airflow can reach the required effective value of 4.83m^3/s when the borehole diameter falls between 410mm and 990mm. In this range, the fan can work in a stable manner.

When the borehole diameter (d_{z0}) was 301mm, the flow requirement cannot be satisfied even if the flow was combined with that of a 211kW fan. Therefore, the ventilation effect should be improved by increasing the length and diameter of borehole or adopting auxiliary ventilation measures.

3.5. Relationship between borehole length and borehole diameter

Considering the difficulty and high cost of drilling ventilation, this subsection explores the relationship between the borehole length and borehole diameter under the stable working range of the fan and changing required airflow. This relationship is fundamental to the rational judgement before drilling ventilation. For the auxiliary fan, the flow resistance in the stable working range can be expressed as Eq.(10):

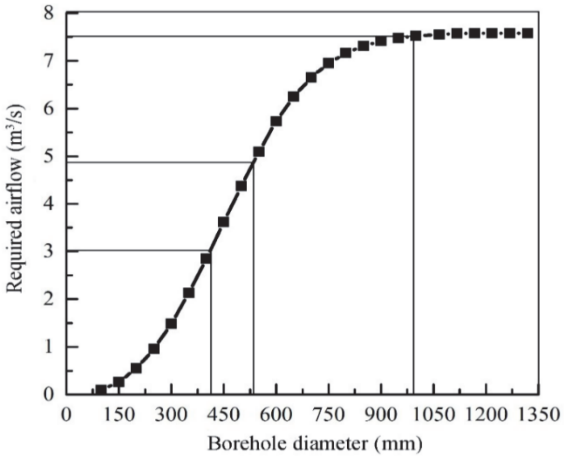


Fig. 4. Effects of borehole diameter on required airflow

$$R_{\min} \le R_z\left(d_z, L_z\right) \le R_{\max} \tag{10}$$

where:

$$R_{\max} = \frac{h_{\max}}{Q_{\min}{}^2}$$

$$R_{\min} = \frac{h_{\min}}{Q_{\max}{}^2}.$$

According to Eq. (10), the relationship between borehole length (L_z) and borehole diameter (d_z) under the stable working range of the fan was plotted as Fig. 5. If the point (L_z, d_z) lies between the $R_{\max}$ curve and the $R_{\min}$ curve, then the fan must be running normally.

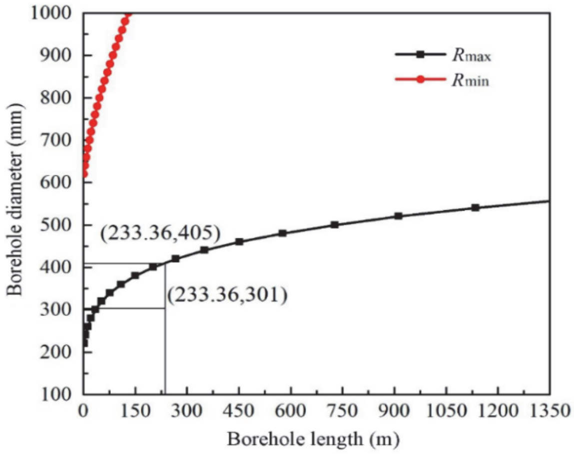


Fig. 5. Relationship between shaft length and shaft diameter under the stable working range of the fan

As shown in Fig. 5, the point (233.36m, 301mm) which represents the borehole length and borehole diameter in the West 1$^\#$ ramp fell below the $R_{\max}$ curve. This means the fan was not running in the stable working range, and the borehole diameter should be expanded over 405mm.

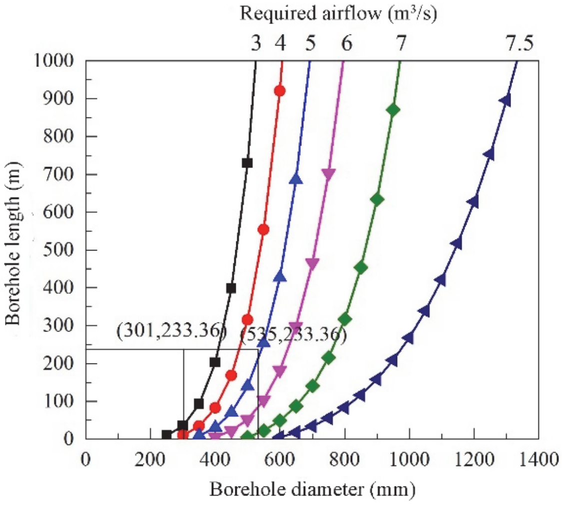


Fig. 6. Relationship between shaft length and shaft diameter at different air flows

According to Eq. (10), the relationship between borehole length and the borehole diameter at different required airflow was drawn as Fig. 6. The required airflow corresponding to the point (233.36m, 301mm) dropped below the required level (4.83m^3/s). In this case, the borehole diameter should be expanded to over 535mm, as the effective airflow can be bolstered by increasing the diameter.

3.6. Effect of borehole position on ventilation

The ventilation system in the mine consists of the drilling ventilation and the transfer ventilation at the bottom as shown in Fig. 1. The transfer fan transports the fresh air to the heading face via the flexible air duct, ensuring the required airflow to the workspace in the tunneling process. The length of the borehole and the location of transfer fan depend on the position of the borehole. To ensure the effect of drilling ventilation, the rated flow Q_f of the auxiliary fan must be greater than (or equal to) the transfer airflow $Q_{transfer}$, i.e. 1.3 times the rated flow of the bottom transfer fan $Q_{f\ bottom}$. The rated flow of the auxiliary fan and the rated flow of the transfer fan can be respectively expressed as Eq. (11) and Eq. (12):

$$Q_f = \frac{\left(-955.56+\sqrt{913086.42+\frac{4\times 7666.67\times R_z\left(d_z,L_z\right)}{p_i}}\right)\square p_i}{2R_z\left(d_z,L_z\right)} \tag{11}$$

$$Q_{f\ bottom} = \frac{\left(-955.56+\sqrt{913086.42+\frac{4\times 7666.67\times R_r\left(d_r,L_r\right)}{p_{ir}}}\right)\square p_{ir}}{2R_r\left(d_r,L_r\right)} \tag{12}$$

where: d_r is the diameter of flexible air duct (m); p_{ir} is the leakage reserve coefficient of flexible air duct ($P_{ir}=\frac{1}{1-n\eta}$); n is the number of concrete sealings ($n=\frac{L_r}{L_p}-1$); L_p is the unit length of flexible air duct (L_p=10m); η is the leakage rate per concrete sealing (η=0.005).

Under 1$^{\#}$ ramp conditions, the relationships between the transfer airflow and transfer distance, incoming airflow and borehole length, effective airflow and borehole length, as well as effective airflow and transfer distance are illustrated in Fig. 7.

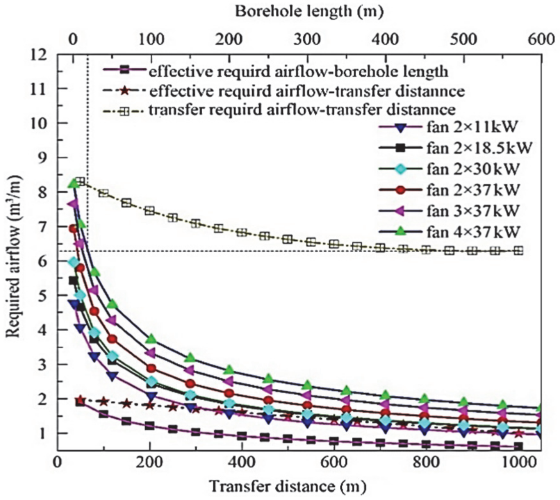


Fig. 7. Relationships between transfer flow and transfer distance, incoming flow and shaft length, effective flow and shaft length, as well as effective flow and transfer distance

Obviously, the transfer airflow decreased in the range of 8.3~ 6.3m^3/s with the growth in transfer distance; the incoming airflow deceased in the range of 4.75~0.8m^3/s with the growth in the borehole length (>56m). The transfer airflow always stays above the borehole airflow. The imbalance of the airflow causes the foul air to circulate at the transfer fan.

Next, the auxiliary fan capacity was increased to 2×37kW, 3×37kW and 4×37kW (parameters as shown in Table 1). The incoming airflow and the transfer airflow could reach a balance after the increasing, but the length of the borehole can only be limited to 20 meters. Under the current borehole diameter, it is difficult to balance the required airflow with borehole airflow by changing the routs length or increasing the fan capacity. Increasing the borehole diameter is a good way to achieve balance.

To increase the required airflow and preventing the circulation of foul air, it should be enhanced the concrete sealings between the borehole and the fan. The entire system forms interval series ventilation by a two-stage fan. After the joint operation, the relationship between required airflow effectivity and borehole parameters that reaching the heading face. In Fig. 7, the airflow is peaked at 1.98m^3/s, indicating that the current borehole is just property to as a auxiliary ventilation method. The borehole length (L_{z0}) was 233.36m, the transfer distance (L_{z0}) was 858m, and the effective airflow was 1.4m^3/s.

Under the above conditions, the relationships between the transfer airflow and transfer distance, incoming airflow and borehole length, effective airflow and borehole length, as well as effective airflow and transfer distance are given in Fig. 8. When the borehole diameter (d_{z0}) was 301m and the transfer distance (L_{r0}) was 858m, the incoming airflow and the transfer airflow were 1.5m^3/s and 6.12m^3/s, respectively. Due to the lack of incoming airflow, there was a circulation of foul air (4.62m^3/s) near the transfer fan, and the effective airflow at the heading fact was 2.35m^3/s.

Under constant fan capacity, the transfer distance was 260m and the effective airflow was over 4.83m^3/s, when the borehole diameter surpassed 830mm; the transfer distance was shorter than 185m and the incoming airflow was smaller than the transfer airflow, when the borehole diameter was 1,000mm, resulting in the circulation of foul air. In this case, the fan has reached the maximum capacity and should be re-selected. As shown in Fig. 8, when the auxiliary fan had a power of 2×30kW and the borehole diameter was 665mm, the transfer distance fell between 50~250m and the effective airflow was enough to prevent the circulation of foul air.

4. Conclusions

In drilling ventilation, the effective required airflow is increasing with the increasing of borehole length and borehole diameter. The increasing ceases when the airflow reaches the saturation point. Beyond this point, the maximum airflow depends on the fan capacity. The ventilation effect can be improved by increasing the borehole length between 0 and 200m. When the length falls 100~650m, the ventilation effect can be enhanced by expanding the borehole diameter.

Effective airflow was enough to prevented the circulation of foul air when the auxiliary fan had a power of 2×30kW, the borehole diameter was 665mm, and the transfer distance fell between 50~250m. The transfer fan at the bottom of the borehole should be replaced if the transfer distance reach to 858m, and the drilling ventilation system should be modified according to the relationship between the transfer airflow and the transfer distance. Changing borehole diameter is more effective on improvement of ventilation effect than increasing fan capacity or reducing transfer distance. As a result, preference should be given to large borehole diameter. Before drilling the borehole, the relationship between L_z and d_z should be studied to predict the effectiveness of the drilling ventilation system under the stable working range of the fan and at different incoming airflows.

Table. 1. Required airflows of auxiliary fans

Auxiliary Fan Type	***Rated Power (kW)***	***Designed Total Pressure (Pa)***	***Designed Flow Quantity (m^3/min)***	***Diameter of Outlet (mm)***
FBD№5.6	2×11	4800-500	180-450	560
FBDY№6.0/2×18.5	2×18.5	5500-450	250-500	610
FBDY№6.3/2×30	2×30	6300-460	260-630	640
FBDY№6.7/2×37	2×37	6500-920	410-730	684
FBDY№6.7/3×37	3×37	9000-1200	410-730	684
FBDY№6.7/4×37	4×37	11600-1480	410-730	684

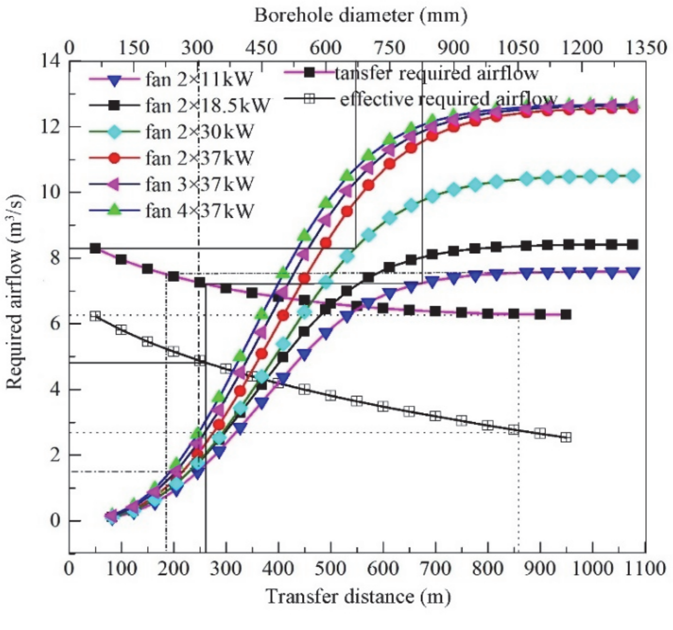


Fig. 8. Relationships between transfer flow and transfer distance, drilling air volume and shaft length, effective flow and shaft length, as well as effective flow and transfer distance

The characteristic curve is no longer linear outside the stable working range of fan, but the outlet airflow of the borehole was estimated as 0.9954m^3/s in the West 1$^\#$ auxiliary ramp, which is close to the actual flow of 0.7118m^3/s. The future research will explore the drilling ventilation effect outside the stable working range. Drilling ventilation is only suitable for the case when long-distance airway construction cannot be achieved ventilation effect by traditional methods.

It is not necessary if other management methods and ventilation measures are available. Compared with conventional excavation construction methods, the additional cost of drilling ventilation technology is mainly concentrated on the following aspects: (1) Equipment and material costs, such as auxiliary ventilator, iron duct (or large diameter steel pipe), joints, cement mortar. (2) The construction cost is mainly reflected in the grouting and sealing of the borehole. (3) After on-site construction is completed, the ground drilling management expenses will be spent.

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