Indexed in
Scopus Compendex and Geobase Elsevier, Chemical Abstract Services-USA, Geo-Ref Information Services-USA, List B of Scientific Journals, Poland, Directory of Research Journals

www.cafetinnova.org

International Journal of Earth Sciences and Engineering

April 2015, P.P.238-244

ISSN 0974-5904, Volume 08, No. 02

Influencing Factors Analysis on Drilling Ventilation Effectiveness in Long-distance Driving Face

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Abstract: To make the ventilation drilling effectively serve for the long-distance driving face, resistance-pressure energy balance equations were established to determine the actual operating condition of the drilling ventilation, based on which the variable relationships among the drilling diameter, the drilling length, the drilling location and the effective air quantity of the working face were discussed , and the restrictive relationships between the drilling length and the drilling diameter were established under the fan stability working range and under different air quantities. The results indicate that effective air quantity decreases while Lz increases, and increases with the increase of dz, but exits an air supply saturation point. When the drilling length ranges from 0-200 m, changing the length is the effective method for conditioning the ventilation effect, and when the drilling diameter ranges from 100-650 mm, changing the diameter is the effective method for conditioning the ventilation effect. For the present whole drilling ventilation system, it is hard to balance the transfer air quantity and the drilling air quantity by decreasing the drilling length or raising the fan capacity. The effective air quantity can reach to 1.4 m3/s after the two fans of the drilling ventilation system are transformed to indirect series connection. Under the conditions that the fan of the drilling is 2×30 KW and the drilling diameter is 665 mm, the effective transfer length can change from 50-250 m. Enlarging the drilling diameter is an effective means to raise the air quantity of the drilling ventilation. Using the restrictive relationship between Lz and dz can predict the effectiveness of the drilling ventilation.

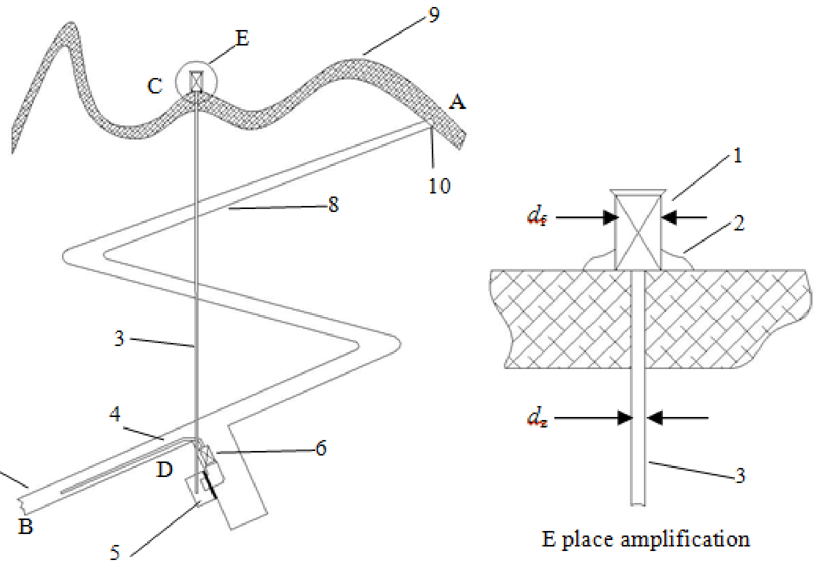
Keywords: *drilling ventilation; long -distance driving; drilling length; drilling location; effectiveness; predict*

1. Introduction

In the process of developing tunnel drivage of metal mine, transport ramp often runs through each level, the ramp route is long, some of them reach more than 2600 m, facing with ventilation route length [1, 2, 3], high resistance [4], air leakage [5], and a series of difficult problems [6, 7]. In this regard, on the basis of traditional way of ventilation, the scholars proposed drilling ventilation technology [8], which alleviates the ventilating pressure of the long tunnel drivage, but it involved a series of questions, such as high construction cost, the ventilation drilling failure and so on, which caused economic loss. As for the study on technology of drilling ventilation, Qing-quan Lin [9], Shan-qi Lei [10], Hong-ying Zhang [7] and other authors proposed how to deal with long tunnel ventilation problems of drilling near the middle of tunnel drivage or surface. Han-chun Teng [11] expounded the principle of ventilation, construction technology, he thought that drilling ventilation was suitable for long tunnel drivage ventilation problem, but the cost of construction is too high. Ya-ping Yang [12] aims at the single end tunnel drivage, proposed ventilation technology of drilling combined with wind library, compared with technical and economic of single air duct and ram ventilation, he thought that drilling ventilation management and effect is good, but the cost is high. From above paragraphs, at present the research on drilling ventilation technology is mainly in the phase of engineering application, the support of essential theory is on the lack, which doesn't ensure effective drilling ventilation. From construction aspects, power of drilling ventilation, length and diameter of drilling are the bottleneck of ventilation. In this paper, resistance-pressure energy balance equations were established to analyze effectiveness of drilling ventilation, which determines the drilling construction conditions to meet the demand of ventilation, effective drilling ventilation was applied to long tunnel drivage by the influence factors such as length and diameter of drilling.

2. Principle of drilling ventilation

Drilling ventilation is construction ventilation which drills from the surface of the earth or middle in the process of developing tunnel drivage in mine, replacing the air supply method that single end tunnel entry directs to heading face, the main technical characteristic is that the ventilation distance is short. Internal of drilling is used a metal sleeve, auxiliary fan directly transfers wind library from the top to the bottom, the junction is sealed by concrete. At the bottom of the drilling, transferring fan takes air into the heading face. Drilling ventilation system schematic diagram in a metal mine is shown in figure 1, the length of A-B segment (traditional ventilation method) is 2400 m, the drilling length of C-D-B segment is 1091.36 m, and so drilling ventilation shortens greatly the distance of ventilation.



1- drilling fan; 2- sealed by concrete; 3- ventilation drilling; 4- flexible air duct; 5- transfer wind library; 6- transfer fan; 7-driving face; 8- ramp of transportation; 9- surface; 10- ramp inlet; d_f- diameter of fan; d_z- diameter of drilling

Fig1. *Drilling ventilation system in long-distance driving*

3. Operating condition determination of drilling ventilation system

3.1. Air flow resistance of ventilation

Ventilation drilling adopts the seamless welding metal pipe to insert vertically into the tunnel, regardless of air flow resistance of joints and elbows, the air flow resistance $R_z(d_z, L_z)$ of drilling will be

$$R_z(d_z, L_z) = \frac{\alpha L_z U_z}{s_z^{\,3}} + \xi_{on} \cdot \left(\frac{\rho}{2s_z^{\,2}}\right) + \xi\left(\frac{d_f^{\,2}}{d_z^{\,2}}\right) \cdot \left(\frac{\rho}{2s_f^{\,2}}\right) \quad (1)$$

Because the roughness of metal air duct internal wall is merely related to its diameter [13], in order to analyze the relationship between diameter of drilling and ventilation effectiveness, we make a regression analysis on the data relationships of α and the diameter of drilling [13] (as space is limited, we will not discuss it), the regression equation is obtained, which is shown in Eq. (2).

$$\alpha(d_z) = 0.0062e^{-1.194 d_z}, \quad R^2 = 0.994 \quad (2)$$

The difference between diameter of drilling fan outlet and diameter of drilling will produce local resistance, thus we make a regression analysis on the data relationship of diameter ratio and the local resistance coefficient [13], and the relationship can be given as

$$\xi\left(\frac{d_f^{\,2}}{d_z^{\,2}}\right) = \begin{cases} 0.9468 \cdot \left(\frac{d_f^{\,2}}{d_z^{\,2}}\right)^2 - 1.9323 \cdot \left(\frac{d_f^{\,2}}{d_z^{\,2}}\right) + 0.9818, & \frac{d_f^{\,2}}{d_z^{\,2}} \in [0,1], \; R^2 = 0.9989 \\ 0.13285 \cdot \ln\left[10.57491 \cdot \ln\left(\frac{d_f^{\,2}}{d_z^{\,2}}\right)\right], & \frac{d_f^{\,2}}{d_z^{\,2}} \in [1,100], \; R^2 = 0.9989 \end{cases} \quad (3)$$

The bottom transfer ventilation system usually adopts flexible air duct. Air flow resistance of joints and on-way are replaced by hectometer air flow resistance, the air resistance of transfer fan R_r is

$$R_r = \frac{R_{100} \cdot L_r}{100} + \Sigma\xi_{bei} \cdot \left(\frac{\rho}{2s_r^{\,2}}\right) + \xi_{on} \cdot \left(\frac{\rho}{2s_r^{\,2}}\right) \quad (4)$$

where $R_z(d_z, L_z)$ is the air flow resistance of drilling, $N \cdot S^2/m^8$; d_z is the diameter of drilling, m; L_z is the length of drilling, m; α is the friction resistance coefficient of air duct, $N \cdot s/m^4$; U_z is the perimeter of drilling, m; s_z is the cross-sectional area of drilling, 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 drilling junction, s_f is the cross-sectional area of body of fan, m^2; R^2 is the goodness of fit, R_r is air flow resistance of ventilation of transfer fan,

$N \cdot S^2/m^8$; R_{100} is the hectometer air flow 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.

3.2. Condition of the Air Supply

The general form of fan operation condition is based on calculating the required airflow of heading face and the air flow resistance of air duct (RQQ_f, Q_f) [14], for auxiliary fan, it is hardly to be given characteristic curve, so the actual fan operation condition usually disagrees with the point (RQQ_f, Q_f), even on the low side. To judge the actual condition of the supply air, according to the designed parameters of the fan, two operating point (h_{max}, Q_{min}) and (h_{min}, Q_{max}), Q_f and h_f are obtained by linearity interpolation of fan characteristic curve, the linear function that changing relationship between Q_f and h_f was depicted approximately local fan running characteristics. Characteristic curve of resistance according with Q_f is related h_f with quadratic equation, therefore resistance-pressure energy balance equations are established, which is shown as Eq. (5).

$$\begin{cases} h_f = \dfrac{Q_f - Q_{max}}{Q_{min} - Q_{max}} h_{max} + \dfrac{Q_f - Q_{min}}{Q_{max} - Q_{min}} h_{min} \\ h_r = RQ_f Q = \dfrac{RQ_f{}^2}{p_i} \end{cases}$$

Where $Q_f \in (Q_{min}, Q_{max})$. When fan works stably, there is $h_f = h_r$. At this time, the air quantity Q_f is the practical working air quantity of the fan. Air quantity Q is the air quantity at air duct outlet, Q is also the effective air quantity which reachs the heading face, which is shown in Eq. (6).

$$\begin{cases} Q_f = \dfrac{(m+\sqrt{n})p_i}{2R} \\ Q = \dfrac{Q_f}{p_i} \end{cases} \Leftrightarrow \begin{cases} Q_f = \dfrac{50(m+\sqrt{n'})p_i}{R_{100} \cdot L} \\ Q = \dfrac{Q_f}{p_i} \end{cases} \quad (6)$$

Where

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

where R is the air flow resistance of air duct, $N \cdot S^2/m^8$; Q is the effective flow quantity which is put into the working face, m^3/s; Q_f is the working flow quantity of the fan, m^3/s; h_{max}, h_{min} is the maximum and minimum designed total pressure of fan, Pa; Q_{max}(Q_{min}) is the maximum (minimum) designed flow quantity of the fan, m^3/s; p_i is the leakage reserve coefficient of air duct; L is the length of air duct, m.

In the Xi-yi auxiliary ramp of a mine, the length of ventilation drilling (L_{z0}) is 233.36 m, the diameter (d_{z0}) is 301 mm (pumping drilling reformed to ventilation drilling, non-standard diameter), the power of auxiliary fan is 2×11 KW, the designed flow quantity range is 180-450 m^3/min, the designed total pressure range is 4800 to 500 Pa, the measured p_i is 2.07, the estimated air quantity at drilling outlet is 0.9954 m^3/s, and very near to the actual air quantity (0.7118 m^3/s)(though fan operation condition is not within the stable working range), it is feasible to use the Eq. (6) to determine approximately the condition of the air supply.

4. Analysis of Influencing Factors on Drilling Ventilation Effectiveness

4.1. Influence of Drilling Length on Independent Drilling Ventilation Effectiveness

Length of ventilation drilling is one of the important factors which influence ventilation effectiveness, according to Eq.(6) we get that the changing relation of drilling ventilation effectiveness and the length of ventilation drilling conform to Eq. (7).

$$Q_f = \frac{\left(-955.56 + \sqrt{913086.42 + \dfrac{4 \times 7666.67 \times R_z(d_{z0}, L_z)}{p_i}}\right) \cdot p_i}{2R_z(d_{z0}, L_z)} \quad (7)$$

Assuming that the sealing effect of drilling and fan joint is ideal, and there is no leakage, so the p_i is 1. From the figure 2, the effective flow quantity is dropped with the length of drilling improving. The range of 0-200 m decreases rapidly. The range of the drilling length is 0-200 m, adjusting the drilling length is an effective measure for improving effect of ventilation. In the current length of drilling, L_{z0} is 233.36 m, when air reaches the bottom of drilling, the effective flow quantity is only 1.5 m^3/s, far less than theoretical flow quantity 4.83 m^3/s, the flow quantity is not able to meet the requirement. Within the scope of the designed theoretical flow quantity of fan, if the length of drilling is 1 m, the effective flow quantity is 4.8 m^3/s. It is meaningless to say that drilling is useful, because the length of drilling is short. When the diameter of drilling d_{z0} is 301 mm, the effective flow quantity of 2×11 KW fan combined with the drilling cannot satisfy the requirement. If improve effect of ventilation, it should raise the diameter of drilling and flow quantity, or use the drilling ventilation as auxiliary ventilation measures.

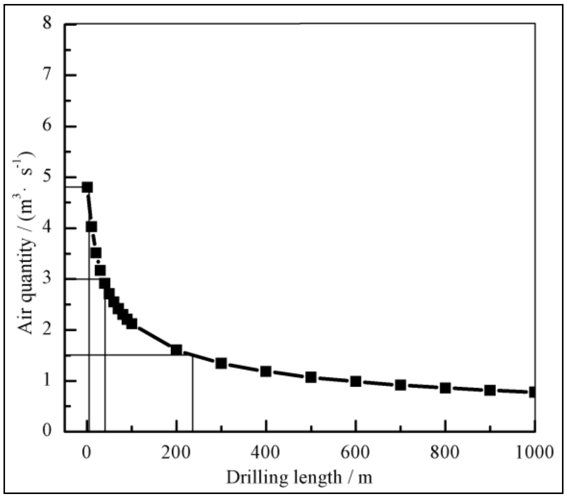


Fig2. *Influence of drilling length on drilling air quantity*

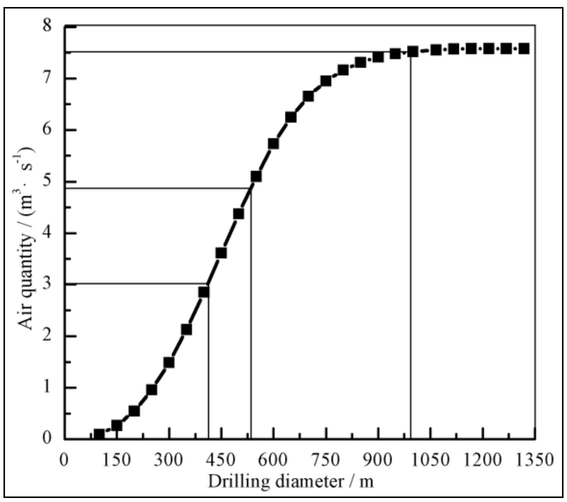


Fig3. *Influence of drilling diameter on drilling air quantity*

4.2. Influence of Drilling Diameter on Effectiveness of Independent Drilling Ventilation

When the length of ventilation drilling is limited, the diameter of ventilation drilling is one of the important factors which influences ventilation effectiveness, the relation of the length of drilling and drilling effective flow quantity conform to Eq. (8).

$$Q_f = \frac{\left(-955.56 + \sqrt{913086.42 + \dfrac{4 \times 7666.67 \times R_z(d_z, L_{z0})}{p_i}}\right) \cdot p_i}{2R_z(d_z, L_{z0})} \qquad (8)$$

In figure 3, the length of drilling (L_{z0}) is 233.36 m, it shows the changing relation of the length of drilling and flow quantity of drilling. The flow quantity of drilling increases rapidly with the diameter of drilling range of 100-650 m increasing. When it reaches to 650 mm, flow quantity of drilling is increased slowly, and it tends to be stable after increasing to 990 mm (maximum flow quantity of designed fan is 7.5 m^3/s). It shows that the diameter of drilling increases to 990 mm, the capacity of fan reaches to saturation, continuing to increase the diameter which can't raise flow quantity of drilling. Increasing the diameter of drilling to adjust the optimal range of the diameter is between 100 and 650 m. Under the current length, the diameter reached to 535 mm, the effective required flow quantity of theory reached to 4.83 m^3/s, the diameter range is 410-990 mm, fan is ensured in stable working range. Figure 3 shows that effective flow quantity is increased with the increasing diameter, and the grads become greater, thus increasing the diameter of drilling is one of the effective ways to solve the problem of drilling ventilation.

4.3. Changing Relation between the Effective Length of Drilling and the Diameter

Because drilling construction is difficult and the cost is high, in order to ensure the effectiveness of the ventilation drilling, we build the changing relation between the length of drilling and the diameter of drilling under the conditions of stable working range and different supply flow quantity. Before the drilling, we make reasonable judgement, so the drilling ventilation effectiveness is ensured.

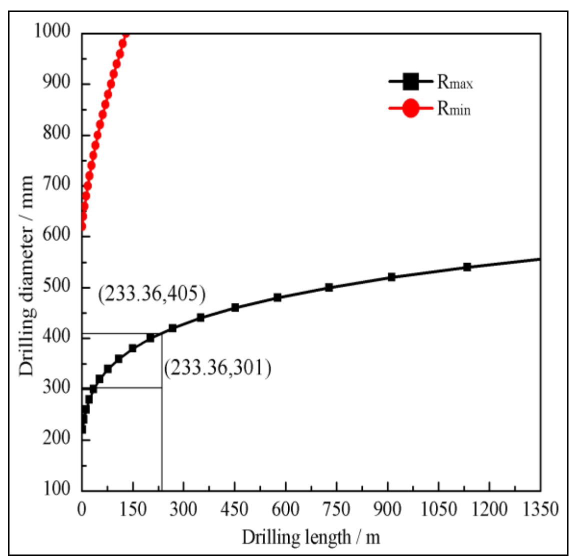


Fig.4 *Corresponding changing relationship between drilling length and drilling diameter under the fan stability working range*

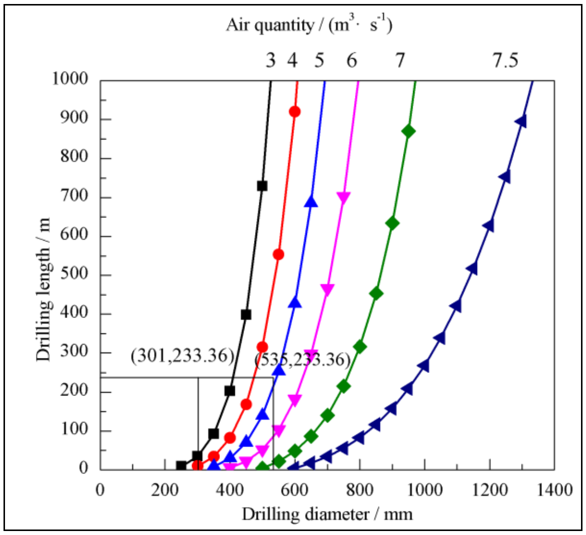


Fig.5 *Corresponding changing relationship between drilling length and drilling diameter under different drilling air quantities*

For an auxiliary fan, within stable working range there would be Eq. (9),

$$R_{\min} \le R_z(d_z, L_z) \le R_{\max} \qquad (9)$$

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

According to Eq. (9), we can build the changing relation of L_z and d_z of fan within stable working range(Fig.4). The point of (L_z, d_z) is located above curve of $R_{\max}$ and below curve of $R_{\min}$, the fan is able to run normally. The figure shows the point (233.36, 301) of making up of the Xi-yi auxiliary ramp current length and the diameter of the drilling is located below curve of $R_{\max}$, so you can judge the fan without stable working range, the diameter of drilling should be expanded to more than 405 mm.

According to Eq. (6), we can build the changing relation of the diameter of the drilling and the length of drilling under the condition of different supply flow quantity. The point of (301, 233.36) which makes up of the Xi-yi auxiliary ramp current length and the diameter of the drilling corresponds to flow quantity will decrease less than required theoretical flow quantity 4.83 m^3/s. The diameter of drilling should be expanded to more than 535 mm. So increasing the diameter can improve the effective flow quantity.

4.4. Influence of Drilling Position on Effectiveness of Drilling Ventilation System

As shown in figure 1, the whole drilling ventilation system is included the drilling ventilation and the bottom ransfer ventilation. The bottom fan transports fresh air to heading face by flexible air duct, to ensure air supply requirement of mine development process. The position of choosing ventilation drilling determines the length of drilling ventilation and bottom fan transfer, and it will affect the fan operation condition. To ensure that the drilling ventilation transit effectively, avoiding transfer fan of bottom of drilling inhales the circular polluted air, the flow quantity should be guaranteed $Q_f \ge Q_{transfer} = 1.3 Q_{f\ bottom}$. Represent flow quantity condition of drilling fan and bottom transfer fan, which is shown in Eq. (10) and (11), to get changing relationship of fan transfer variable and different conditions (Fig.6 and Fig.7).

$$Q_f = \frac{\left(-955.56 + \sqrt{913086.42 + \frac{4 \times 7666.67 \times R_z(d_z, L_z)}{p_i}}\right) \cdot p_i}{2R_z(d_z, L_z)} \qquad (10)$$

$$Q_{f\ bottom} = \frac{\left(-955.56 + \sqrt{913086.42 + \frac{4 \times 7666.67 \times R_r(d_r, L_r)}{p_{ir}}}\right) \cdot p_{ir}}{2R_r(d_r, L_r)} \qquad (11)$$

where $Q_{transfer}$ is transfer flow quantity, m^3/s); $Q_{f\ bottom}$ is the working flow quantity of bottom transfer fan, m^3/s; d_r is the diameter of flexible air duct, m; p_{ir} is the leakage reserve coefficient of bottom flexible air duct ($p_{ir} = \frac{1}{1-n\eta}$), n is the amount of air duct-joint ($n = \frac{L_r}{L_p} - 1$); L_p is the length of one section air duct(the value is 10 m), m; η is the leakage rate of one air duct-joint (the value is 0.005 [13]).

In figure 1, the diameter of drilling (d_{z0}) is 301 mm, the diameter of bottom transfer air duct (d_{z0})is 600 mm, the power of fan are 2 x 11 KW. Getting changing relation of transfer flow quantity and transfer distance, drilling flow quantity and the length of drilling, the effective flow quantity and the length of drilling, the effective flow quantity and transfer distance are shown in figure 6. Transfer flow quantity decreases with increasing transfer distance within 8.3 ~ 6.3 m3/s, drilling flow quantity decreases with increasing the length of drilling (> 50 m)within 4.75-0.8 m^3/s, transfer flow quantity is always above drilling flow quantity, unbalanced flow quantity leads to cycle of foul air at transfer position. Increasing capacity of drilling fan, to apply fan of table 1 in order, fan of 2x37 KW, 3x37 KW, and 4x37 KW can achieve flow quantity balance of transfer and drilling. But the length of drilling can only be set within the 20 m, indicates that changing the length and capacity of fan are difficult to realize balance of transfer flow quantity and drilling flow quantity. It should increase the diameter to change flow quantity under the current the diameter. Under the current condition, in order to improve the supply air rate and avoid circular polluted air, the bottom drilling transfer position strengthens sealing, the whole system form a two-stage series fan, after joint operation, change relation of effective flow quantity at heading face and the length of drilling, effective flow quantity and transfer distance as shown in figure 5. The largest flow quantity is only 1.98 m^3/s, so the current drilling system is appropriate as auxiliary ventilation measures. Under the condition of fan joint operation, the length of drilling (L_{z0}) is 233.36 m and transfer distance (L_{z0}) is 858 m, effective flow quantity is 1.4 m^3/s.

Table 1 *Characteristics 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

Figure 7 shows that the changing relation of transfer flow quantity and the length of drilling, the effective flow quantity and transfer distance, transfer flow quantity and transfer distance. Under the current condition of the diameter of drilling (d_{z0}) is 301 m and transfer distance (L_{r0}) is 858 m, drilling flow quantity is 1.5 m^3/s and transfer flow quantity is 6.12 m^3/s.

Because of inefficient drilling flow quantity, there is circular polluted air of 4.62 m^3/s near the transfer fan, and the effective flow quantity is 2.35 m^3/s at heading face. Under the current capacity of fan, when the diameter of drilling is greater than 830 mm, transfer distance is equal to 260 m, the effective flow quantity is more than 4.83 m^3/s. If the diameter of drilling is 1 000 mm, transfer distance is less than 185 m, drilling flow quantity is less than transfer flow quantity, circular polluted air will appear. It shows that capacity of fan has reached saturation, and should reselect matching fan.

Above the figure, when the power of drilling fan is 2×30 KW, the diameter of drilling is 665 mm, they can guarantee the effective flow quantity when the distance between the development drivage and the bottom of the drilling within the scope of 50-250 m, no appear insufficient air supply required and circular polluted air.

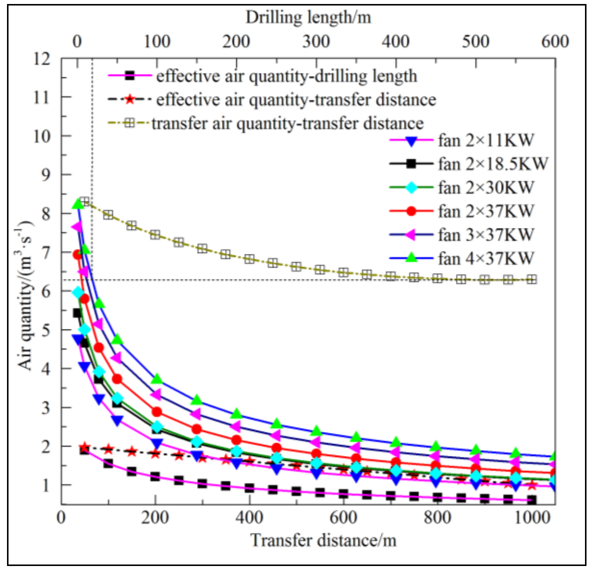


Fig.6 *Relationships among transfer air quantity and transfer distance, drilling air quantity and drilling length, effective air quantity and drilling length, effective air quantity and transfer distance*

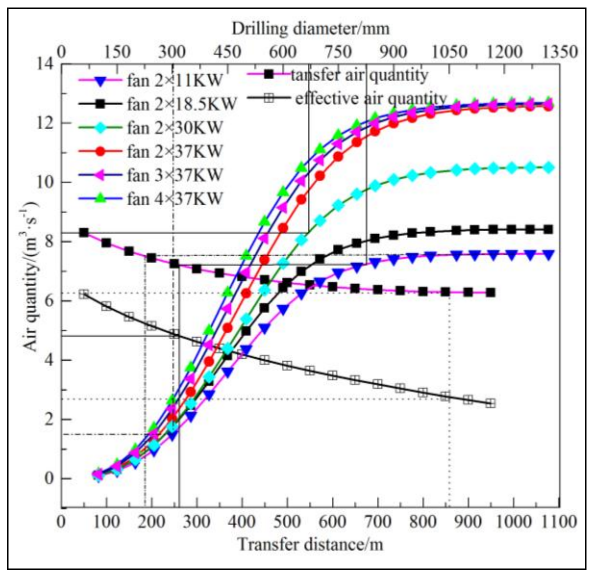


Fig.7 *Relationships among drilling air quantity and drilling diameter, effective air quantity and transfer distance, transfer air quantity and transfer distance*

5. Conclusions

(1) The effective flow quantity decreases with increasing the length of the drilling, the effective flow quantity increases with increasing of the diameter of drilling, but there is the critical point that flow quantity reaches saturation, and maximum flow quantity of the drilling ventilation depends on capacity of fan. It is efficient for changing the length to improve ventilation effect, when the length of

drilling range is between 0 and 200 m. When the length of drilling range is between 100 m and 650 m, it is efficient for changing the diameter to improve ventilation effect.

(2) The power of drilling fan is 2×30 KW, the diameter of drilling is 665 mm, they can guarantee the effective flow quantity when the distance between the development drivage and the bottom of the drilling within the scope of 50-250 m, insufficient air supply required and circular polluted air are not appearred. If the distance wants to meet 858 m, transfer fan of bottom of drilling must be replaced, to establish curve of changing relation of transfer flow quantity and transfer distance and use the same method to determine drilling ventilation system.

(3) Comparing with improving capacity of fan and shortening the distance of ventilation, it is efficient for changing the diameter to improve ventilation effect. So the drilling of large-diameter is selected in preference. In order to ensure effectiveness of drilling ventilation, before digging ventilation drilling, to establish curve of L_z and d_z to pre-judge effectiveness of system for stable working range and different supply flow quantity.

(4) The characteristic curve that no longer subject to linear distribution outside stable working range of fan. Further research should be done to make sure the curve outside stable working range of fan, the curve may be only available for reference. But the verification results of the Xi-yi auxiliary ramp show that estimated flow quantity 0.9954 m^3/s is near to the measured flow quantity 0.7118 m^3/s.

6. Acknowledgments

The authors are grateful to editors and anonymous referees for their very valuable comments and suggestions, which have significantly helped improve the quality of this paper. Meanwhile, this paper is supported by The Project Supported by National Natural Science Foundation of China (No. 51204089) and the scientific research project of Education Department of Liaoning Province (No. L2014131).

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