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Optimization of bit nozzle parameters of reverse circulation sampling used in coal mines

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ABSTRACT
The coal mine air reverse circulation sampling technique is important for improving the accuracy of direct determination of gas content. The sampling drill is an important structural element to realize this technique. The embedded annular ejector and external nozzle of the drill are the main structures that can achieve reverse circulation. The external bit nozzle divides the mine compressed air into two parts. One part is used to wash the drill hole in order to prevent hole collapse, and the other part can press cuttings at the hole bottom into the drill pipe center tube and provide the transmission power. Bit nozzle dip angle and position are studied by numerical simulation, and the results are proved by the filed test. The results show that when the dip angle of the nozzle is 15° and the position is appropriate away from the drill cutter, the reverse circulation is better and the sampling depth increases. This improves the quality of sampling and prevents damage to the drill bit and buried drill accidents.
KEYWORDS: Coal mines; reverse circulation sampling; bit nozzle; numerical simulation

1. INSTRUCTIONS

The air reverse circulation sampling technique is widely used in the geological prospecting industry in China and other countries, as it is a kind of sampling technique with large sampling depth, high sampling rate, spot sampling, low sample contamination rate, and strong representation. In this technological field, Jilin University has formed a series of specifications for reverse circulation drilling equipment (Zhang et al., 2007). Due to the advantages of the technique, from the year 2005 to 2010, the CCTEG Xi’an Research Institute in China and the Commonwealth Science and Industries Research Organization (CSIRO) in Australia used it for coal sampling in mines, in order to improve the accuracy of direct determination of gas content of coal seams. Because the drilling cuttings stress state and the mine air pressure in the coal seam borehole is different from the geological prospecting borehole, the sampling depth of the underground coal mine air reverse circulation equipment has not been able to effectively break through 60 m (Yuan et al., 2011; Yuan et al., 2014; Hu, 2011). From the year 2011 to 2015, the China Coal Technology Engineering Group Chongqing Research Institute (Referred to as Chongqing Research Institute) developed the SDQ type deep hole fixed-point sampling device (Li, et al, 2014 and Zhang, 2014), increased the depth of coal mine air reverse circulation sampling to 120 m, which has provided the technical and equipment support for the accurate determination of gas content in large inclined long coal mining working faces. The sampling drill designed by Chongqing Research Institute leads the drilling cuttings from the bottom of the hole into the double-wall drill pipe inner tube by the effect of center tube extraction under external pressure (Zhang et al., 2014). The external bit nozzle is an important structure for providing the external pressure. Based on computational fluid dynamics (CFD) and field tests, this study will probe into the optimum design of the dip angle and position of the external nozzle, in order to enhance the effectiveness of reverse circulation sampling.

2. THE MECHANISM OF THE UNDERGROUND REVERSE CIRCULATION SAMPLING BIT

A sampling bit with internal and external jet flow control (air flow) functions is developed with reference to the air reverse circulation sampling bit in the geological exploring industry and previous research results and according to the characteristics of drilling sampling in current underground coal seams, as shown in Figure 1. The sampling bit adopts a composite design, that is, the annular ejector with an internal injection function is embedded in the inside of the drill bit, a positive pressure injection orifice with external injection function is installed outside the side wall, and the end head designed to be

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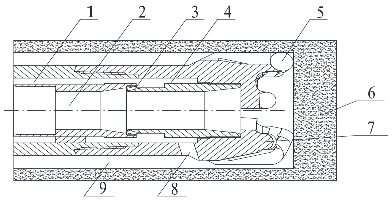
a cutting structure of cuttings granularity control with an anti-blocking type. This structure can make the fresh cuttings automatically adjust to be the gas-solid two phase flow with appropriate solid-gas ratio and flow rate, according to the change of drilling resistance, under the triple control of external collection, internal extraction, and hole wall shunting. The fresh cuttings then enter the center pipe of double-wall drill pipe to form the reverse circulation. The principles of underground reverse circulation sampling are shown in Figure 2.



1-annular space, 2- center pipe, 3- jet nozzle, 4-annular ejector, 5-drilling cutter, 6-coal wall, 7- bit body, 8- external bit nozzle, 9-gap between the drill bit and hole wall

Figure 1: The structure of sampling bit with internal and external jet flow control.

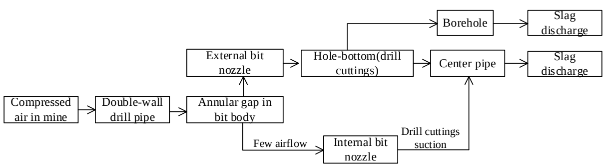


Figure 2: The mechanism of the underground reverse circulation sampling.

As can be seen from Figure 2, the borehole wall shunts compressed air after it flows through the external bit nozzle. A portion of the gas stream continues to flow to the hole bottom, providing positive pressure power for making the drill cuttings get into the center pipe and cooling the drilling cutter at the same time. Another portion of the gas flows to the nozzle, carrying the residual cuttings to avoid the occurrence of buried drilling accidents. With the gradual increase of the drilling depth, the slag discharge resistance of the drill hole and center pipe increases gradually. It is easy to cause problems such as drilling difficulties, low service life of drill bits and poor effects of reverse circulation sampling, if the air distribution of the two air-return slag discharging space is unreasonable. Therefore, this paper takes the dip angle of the external bit nozzle and hole position as the research object, through a combination of the Fluent numerical simulation and field test method to optimize the two parameters, in order to further improve the effect of reverse circulation sampling under the premise of normal drilling.

3. PARAMETERS OPTIMIZATION RESEARCH OF SAMPLING BIT NOZZLE BASED ON THE NUMERICAL SIMULATION

3.1 Modeling

Because the longitudinal section of the sampling bit is symmetrical, it can be used to study half of the sample structure when researching the parameters of the external bit nozzle. A two-dimensional model was established in order to study the influence of the external nozzle parameters on the reverse circulation effect, as shown in Figure 3. The grid was divided by using gambit. The air inlet is the inlet of compressed air, where the pressure is 0.2 MPa. The outlet1 and outlet2 are for export, and the pressure is the atmospheric pressure.

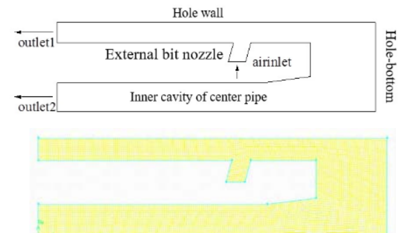


Figure 3: The simplified model and mesh of sampling bit.

3.2 Dip angle optimization of the external bit nozzle

3.2.1 The internal flow field of the model with different dip angle

As shown in Figure 4, α refers to the dip angle of the external bit nozzle, which is defined as the angle between the central axis of the external bit nozzle and the normal which is vertical to the hole wall.

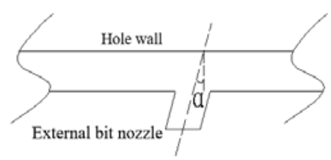


Figure 4: The dig angle of external bit nozzle.

With reference to the design experience of the common drill in the drilling tool industry, the model of different dip angles of the external bit nozzle was set up, with the dip angle α set as 0°, 15°, 25°, 35°, 45°, and 55°. Numerical simulation was carried out using Fluent software, and the distribution of compressed air velocity in the internal flow space of the model was obtained, as shown in Figures 5-10.

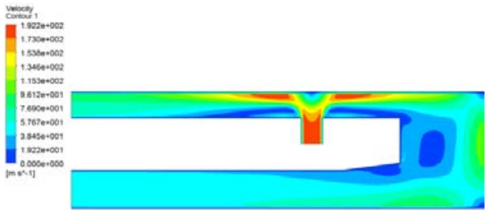


Figure 5: The flow field when dip angle is 0°.

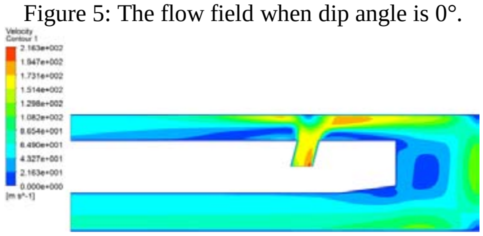


Figure 6: The flow field when dip angle is 15°.

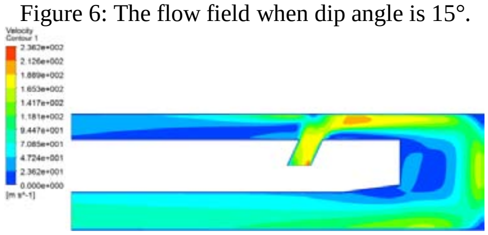


Figure 7: The flow field when dip angle is 25°.

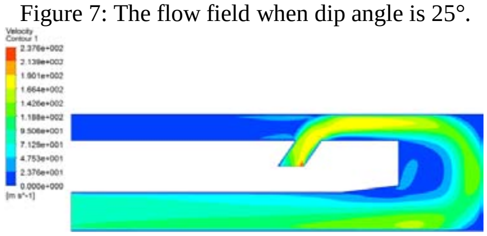


Figure 8: The flow field when dip angle is 35°.

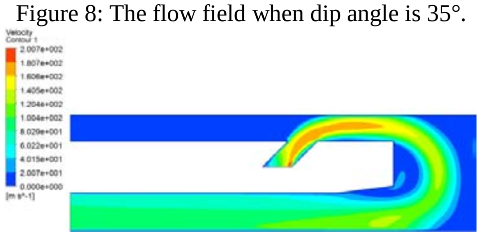


Figure 9: The flow field when dip angle is 45°.

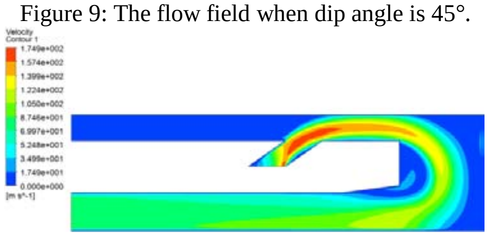


Figure 10: The flow field when dip angle is 55°.

The following observations are made from Figures 5 to 10:

(1) Compressed air jets out from the external bit nozzle flow to the orifices and bottom of drill hole by a rebound off of the borehole wall. With the increase of dip angle of the bit nozzle, the airflow into the bottom increases gradually.

(2) With the increase of the dip angle of the external bit nozzle, the pressure on the hole bottom increases gradually, but the air flow velocity decreases.

3.2.2 The analysis of airflow velocity on the hole bottom

As shown in Figure 11, the center cross section of the drilling cutter near the bottom of hole is taken as the analysis object. The cross section is the most concentrated area of drilling cuttings when cutting coal.

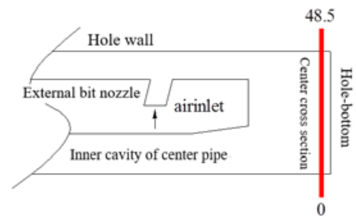


Figure 11: The location of center cross section of the drilling cutter.

The velocity distribution of different locations (range of 0-48.5 mm at hole-bottom line) in the center cross section of the drilling cutter under different dip angles of the external bit nozzle is shown in Figure 12.

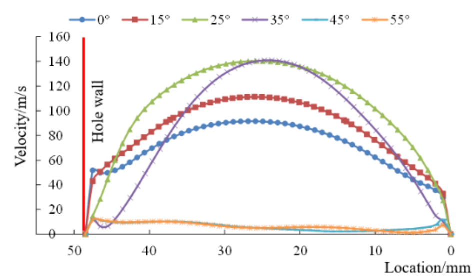


Figure 12: The velocity distribution of different location in the center cross section of the drilling cutter.

It can be concluded from Figure 12 that:

(1) When the dip angle of the external bit nozzle is in the range of 0°-15°, the velocity distribution on the center cross section of the drilling cutter is more uniform, and the air flow is wider through the cross section, which can carry most of the drilling cuttings.

(2) When the dip angle of the external bit nozzle is in the range of 25°-35°, the velocity of air in the center section of the drill cutter reaches a maximum but the distribution is not uniform, and the airflow velocity decreases near the wall of the hole.

(3) When the dip angle of the external bit nozzle is 45° and 55°, the center cross section of the drill

cutter becomes smaller and the velocity becomes less than 15 m/s in most locations, The drilling cuttings at the hole bottom are not easily disturbed at this velocity.

In conclusion, when the external nozzle angle is in the range of 0°-35°, it is conducive to form the reverse circulation which can carry cuttings from the bottom of the hole. However, when in the range of 0°-15°, the air flow in the cross section of the drill cutter is uniform. On the one hand, this is conducive to cooling the drilling cutter, but on the other hand, high-speed airflow can completely cover the area of the hole bottom, giving the drill cuttings easier access to the center pipe to form the reverse circulation.

3.2.3 The analysis of outlet flow rate

As shown in Figure 13, the rate of air flow which flows to the bottom is defined as positive, while flow to the nozzle is negative. According to the simulation results, the air flow rate of outlet1 and outlet2 under different dip angles of the bit nozzle are found, as shown in Figure 14.

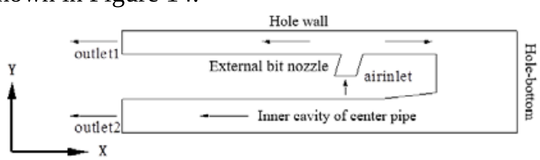


Figure 13: The flow direction in the model inner.

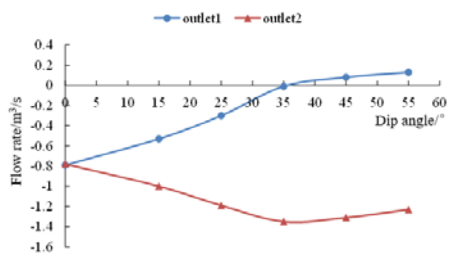


Figure 14: The flow rate of outlet1 and outlet2 changed with the dip angle of the external nozzle.

The following conclusions can be drawn from Figure 14:

(1) When the outlet pressure is the same, the air flow through the external bit nozzle is the outflow from outlet1 and outlet2. When the dip angle of the bit nozzle is 0°, the flow rate of the two exits is the same. With increases of the dip angle, the amount of air flowing through outlet1 decreases gradually, and the air quantity flow through outlet2 increases gradually.

(2) When the dip angle of the external bit nozzle is 35°, the air quantity flow through outlet1 is 0. When the dip angle is greater than 35°, outlet1 not only does not discharge the wind, but snifts the wind. When the dip angle is greater than or equal to 35°, the air quantity flow through outlet2 increases, but in practical application, it is not conducive to the discharge of the hole wall residual cuttings and the phenomenon of buried drill or clamp drill are likely to occur.

3.2.4 The analysis of outlet flow velocity

Figure 15 is the variation diagram of average velocity of the outlet with the change of the dip angle of the external bit nozzle, obtained from the simulation results.

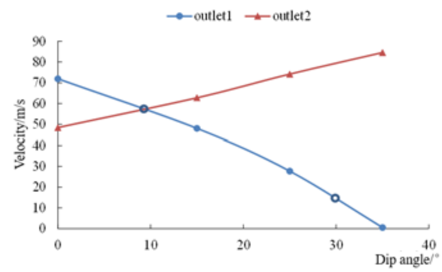


Figure 15: The flow velocity of outlet1 and outlet2 changed with the dip angle of the bit nozzle.

It is can be concluded from Figure 15 that:

(1) When the dip angle of the external bit nozzle is more than 30°, the average velocity of flows through outlet1 is less than 15 m/s. In practical applications, the speed is less than pneumatic conveying speed which is the minimum suspension speed of cuttings, therefore, this dip angle is not conducive to the discharge of residual cuttings, and may cause the phenomenon of buried drill or clamp drill.

(2) When the dip angle of the external bit nozzle is about 10°, flows through outlet1 and outlet2 have the same average velocity. The energy of wind in this angle has reasonable allocation and utilization for carrying drilling cuttings.

Based on the above numerical simulation results, it is concluded that when the dip angle of the external bit nozzle is in the range of 0°-15°, it can form the reverse circulation which is favourable to carry the drilling cuttings. When dip angle is about 10°, the energy of the air flow is reasonably allocated and utilized. Taking into account the actual application process, the smaller the dip angle, the greater the gas etching by the air flow. Dip angles close to 0° are not conducive to the maintenance of the molding and stability of drilling, and should therefore be avoided. At the same time, based on the purpose of sampling which expects to discharge more cuttings through outlet2, practical applications should make the air quantity through the outlet2 slightly greater than outlet1, so the dip angle should be greater than 10°.

By comprehensive analysis, the range of the dip angle of the external bit nozzle should be 10°-15°.

3.3 The determination of location of external jet orifice

On the basis of the optimization of the dip angle of the external bit nozzle, a physical model of the bit nozzle in different locations is established, as shown in Figure 16. The internal flow field of three kinds of situations model was simulated in order to determine the position of the bit nozzle which is the most beneficial in promoting the formation of reverse circulation at the bottom of the hole.

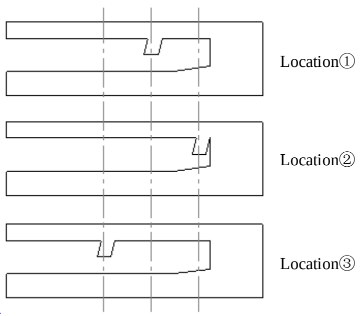


Figure 16: The bit nozzle models of different location.

The velocity images of compressed air in the model are obtained by numerical simulation, as shown in Figures 17 to 19.

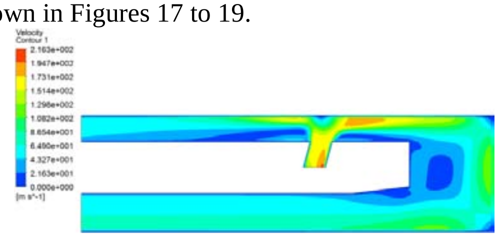


Figure 17: The velocity images when bit nozzle is in location ①.

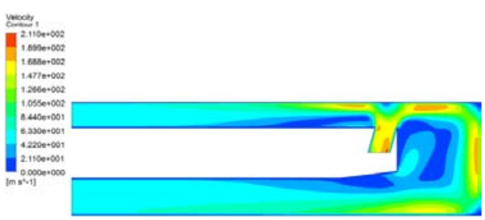


Figure 18: The velocity images when bit nozzle is in location ②.

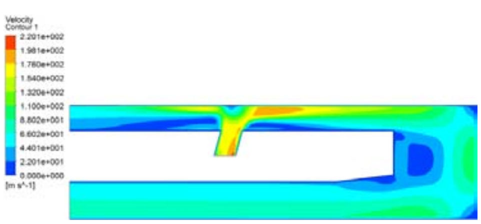


Figure 19: The velocity images when bit nozzle is in location ③.

Data from the analysis of the air flow rate and the average velocity of outlet1 and outlet2 are shown in Table 1. The flow rate through outlet2 is about 65% of the total flow at location ①, about 60% at location ②, and about 66% at location ③. Regardless of the location of the jet orifice, the flow of outlet2 is dominant, while the average velocity of outlet1 and outlet2 is greater than 15 m/s, which can satisfy the transportation conditions of drilling cuttings. Therefore, on the basis of the optimization of the dip angle of the external bit nozzle, the position of the external bit nozzle has little influence on the effect of the reverse circulation.

Table 1: The air flow rate and the average velocity of outlet in different location of the bit nozzle.

Location	Flow rate/m^3/s		Velocity/m/s	
	outlet1	outlet2	outlet1	outlet2
①	0.53	1	48.1	62.8
②	0.61	0.9	55.4	56.2
③	0.51	1	46.1	65.1

The flow lines of space velocity and effective air flow rate are analyzed as shown in Figure 20. When the external bit nozzle is in the three positions, the flow field in the hole bottom are not the same. When the external bit nozzle is at location ①, the vortex area of the hole bottom space is small, and the direction of the air flow velocity is very smooth. When the external bit nozzle is at location ②, the vortex area of the hole bottom space becomes larger, the effective air flow line is mainly concentrated in the vicinity of the coal wall in the hole bottom, and the flow line compression phenomenon is generated. When the external bit nozzle is at location ③, the vortex area of the bottom space is small, but the direction of the airflow velocity is not more smooth than with the bit nozzle at location ①.

In summary, models can be obtained through the simulation of the internal flow field under three kinds of external bit nozzle locations. At the same dip angle of the external bit nozzle, the influence of bit nozzle location on the distribution of the air outflow rate of the model is small, and the outlet velocity can meet the transmission speed of the cuttings. The vortex area of the bottom space has an increasing trend, which is not conducive to make the drilling cuttings from bottom-hole get into the center pipe space to form an effective reverse circulation, when the bit nozzle location is moved forward. Compared with the simulation results, it is concluded that the reverse circulation of the hole-bottom drilling cuttings can be better realized when the bit nozzle location is far away from the drilling cutter.

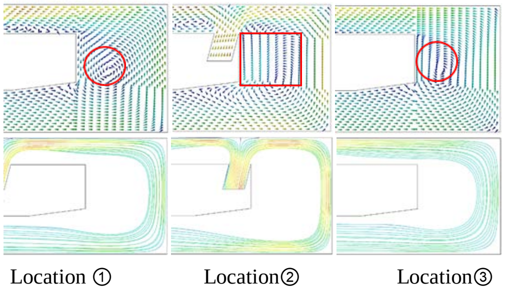


Figure 20: Velocity vector diagram and flow chart of bit nozzle in different position.

4. FIELD TEST

In order to verify the correctness of the numerical simulation results, the diameter of a 95 mm drill was processed according to the above conditions for a real coal mine reverse circulation sampling test. The range of sampling depth, the average sampling quality of single drill pipe, and the drilling situation in the sampling process was investigated, as shown in Tables 2 and 3.

Table 2: The sampling effect of drill bit with different dip angle of the bit nozzle.

Investigation targets / Dip angle (°)	Sample depth/m	Average sampling quality of single drill pipe /Kg	Drilling situation in sampling process
0	80~110	4.2	good slag discharge
15	90~120	5.7	good slag discharge
25	80~90	4.5	good slag discharge
35	50~70	2.1	buried drill
45	20~45	2.2	buried drill
55	20~30	1.7	buried drill

Note: the largest quality cuttings of single drill pipe drill were about 9.3Kg.

According to the field test, it is known that when the dip angle of the external bit nozzle is 15° the inspection parameters are all optimal. At the same time, with the dig angle of the external bit nozzle become larger, the phenomenon of buried drill often happens because the normal drilling in the sampling process cannot be guaranteed. Therefore, the sampling depth is shallow and the sampling quality is low. When the external bit nozzle position is in the three kinds of situations, the sampling depth of the field test is better, but the quality of the sample is less in location ②. The field test is consistent with the numerical simulation results.

Table 3: The sampling effect of drill bit with different locations of the bit nozzle.

Investigation targets / Location	Sample depth/m	Average sampling quality of single drill pipe /Kg	Drilling situation in sampling process
①	90~120	5.7	good slag discharge
②	80~110	2.4	good slag discharge
③	90~120	4.9	good slag discharge

5. CONCLUSIONS

The external bit nozzle of tge sampling bit can split the compressed air in the mine into the hole-bottom space, which is the key configuration for promoting the anti-cyclical effect in the process of sampling, guaranteeing normal drilling slag discharge, and cooling the drill cutter.

The dig angle and the position of the external bit nozzle of the sampling bit was studied through the use of numerical simulation and a field test. The results show that when the dig angle of the external bit nozzle is 15°, the drill cutter can make the sampling bit produce a better anti cyclical effect, increase sampling depth, improve the quality of sampling, prevent bit damage, and prevent the occurrence of buried drill accidents.

6. ACKNOWLEDGEMENT

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