Analysis on structural design and experimental effect of two kinds of hollow-through DTH hammer reverse circulation bits

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ABSTRACT. *The good reverse circulation effect is the key to the reverse circulation drilling of the hollow-through DTH (Down-the-hole) hammer. For this reason, our research group has developed and designed two kinds of new type of reverse circulation bits. Hydrodynamic software is used to comparatively analyze the flow fields of the two kinds of bits. The simulation experiment shows that the slit-type inner nozzle structure has better pumping effect and the speed cloud chart shows that the wall effect of the slit structure is the best, and its flow field is evenly distributed, which greatly reduces the interference effect of the fluid. In Yuanjia Village Iron Mine in Lanxian County of Taiyuan Iron and Steel Group, a field test is conducted on the slit-type inner nozzle reverse circulation bit, indicating an accumulative footage of 43.2m, and drilling efficiency of 12.8m/h or more per hour. The field test shows that the newly developed slit-type reverse circulation bit has good reverse circulation effect, and realizes the highly efficient and fast drilling of hollow-through DTH hammer reverse circulation bit, which has greatly improved utilization performance.*

RÉSUMÉ. *Le bon effet de circulation inverse est la clé du forage à circulation inverse de marteau fond-de-trou (MFT) de pénétration. Pour cette raison, notre équipe de recherche a développé et conçu deux types de nouveaux trépans à circulation inverse. Le logiciel hydrodynamique est utilisé pour analyser de manière comparative les écoulements de champ des deux types de trépans. Le test de simulation montre que la structure de de l'embout intérieur à fente a un meilleur effet de pompage et le graphique de la vitesse en nuage montre que l'effet de la structure à fente est le meilleur et que son écoulement de champs est uniformément réparti, ce qui réduit considérablement l'effet d'interférence de la fluide. Dans la mine de fer du village de Yuanjia situé au comté de Lanxian appartenant du groupe de fer et d'acier de Taiyuan, un test sur le terrain est effectué sur le trépan à circulation inverse de l'embout intérieur à fente, indiquant une longueur cumulée de 43,2 m et et une efficacité de forage de 12,8 m/h ou plus par heure. Le test sur le terrain montre que le trépan à circulation inverse de type fente récemment mis au point a un bon effet de circulation inverse et permet* *de forer de manière extrêmement efficace et rapide le trépan de circulation inverse de marteau fond-de-trou (MFT) de pénétration, ce qui a considérablement amélioré les performances d'utilisation*

KEYWORDS: *reverse circulation bit, hollow-through dth hammer reverse circulation bit, slit-type inner nozzle structure, the double-row inner nozzle structure.*

MOTS-CLÉS: *trépan à circulation inverse, trépan de circulation inverse de marteau fond-de-trou (MFT) de pénétration, structure de l'embout intérieur à fente, structure de l'embout intérieur à double rangée.*

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1. Introduction

With high drilling efficiency, low cost, high sampling rate and other advantages, hollow-through DTH (Down-the-hole) hammer reverse circulation drilling technique is one of the world's advanced drilling techniques, which are widely used in the field of geological drilling, providing an advanced drilling system for mineral exploration and production (Chiang and Elias, 2000). In this drilling system, the reverse circulation bit is a key component for the formation of a reverse circulation, which directly transmits the piston impact force to the rock body to realize the rock fragmentation, achieves the reverse circulation effect through the bottom reverse circulation bit, drives the rock debris at the bottom of the hole into the central channel and to reach the ground through the central channel of the double-wall drill pipe, thus to complete the reverse circulation drilling. The good reverse circulation effect can greatly improve the drilling efficiency and the coring rate, and the removal of the rock debris at the bottom of the hole in time can reduce the repeated crushing of the broken rock, thus ensuring the longer service life of the bit and the performance of the system (Bu *et al*., 2009; Yin *et al*., 2010). Therefore, the optimized design of the reverse circulation bit is essential to improve the reverse circulation effect and the smooth implementation of the reverse circulation drilling process. Our research group has developed and designed two kinds of new type of reverse circulation bits and adopts hydrodynamic software to compare that flow field of the two kinds of bits to optimize the structural parameters and process the test piece. In Yuanjia Village iron mine in Lanxian County of Taiyuan Iron and Steel Group, we have also carried out a field test on the slit-type inner nozzle reverse circulation bit (Bo *et al*., 2011).

2. Principles of reverse circulation bit structure

Figure 1 shows a typical multi-nozzle ejector reverse circulation bit.

The fluid structure of the reverse circulation drill determines the effect of reverse circulation. After the DTH is working, the high-pressure fluid enters the spline groove of the bit tail. The high-pressure fluid is divided into two parts, one part enters the central channel through the inner nozzle 5, and the other part is injected to the nozzle bottom through the bottom nozzle 6. The high-pressure fluid forms a high-speed injection flow through the bottom nozzle 6, which has a strong suction effect on the surrounding low-pressure fluid to form the ejected fluid. The ejected fluid carries rock debris into the diffuser and transfers energy and momentum with the high-pressure fluid so that the ejected fluid has sufficient energy to carry rock debris. The bottom nozzle injects high-speed fluid to form a low-pressure zone, which has strong suction effect on the surroundings, allowing the surrounding fluid to enter the diffuser quickly. The heat generated by the drill bit lip ball impacting the broken rock is transferred to the ejected fluid to cool down the drill bit. The structure of the ring groove 7 is designed to effectively prevent the continued diffusion of part of the fluid to the outer ring gap, thus the injected high-speed fluid and the reflected fluid from the rock can thus stop flowing to the outer ring gap to enter the central channel 4 directly via the flow guide of the diffuser. The mixed fluid entering the central channel slag a large amount of rock debris, and its speed gradually slows down and its pressure rises after further mixing and energy exchange.

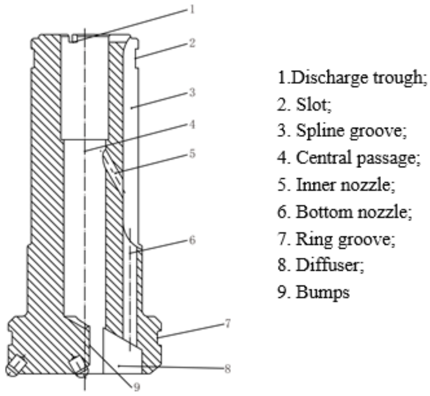


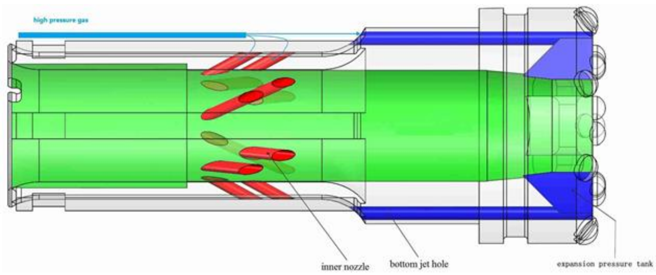
Figure 1. Structure of reverse circulation

Another part of the gas is injected into the central channel 4 at a high speed through the inner nozzle 5. The number of bottom nozzles and the number of inner nozzles should be determined according to the diameter of the drill bit and the air supply volume. The structure design of the inner nozzle is to make an upward inclined hole in the spline groove. The high-speed jet flow is injected upward through the inner nozzle to form a diffuser zone in the upper part and a low-pressure zone in the lower part, wherein the low-pressure zone has a pumping effect on the fluid at the bottom of the drill bit, which greatly enhances the reverse circulation effect. Therefore, the design of inner nozzle can greatly solve the problem of leakage when drilling to extremely broken formation and leaking formation, improves the ability of the upper return fluid to carry rock debris, and reduces the repetitive breakage by drill bits on the rock debris, thus the drilling efficiency and the service life of the bit are greatly improved, and the accident rate of blocking is reduced. The structure design of bit has great influence on the overall performance and safety of drilling tool system. At the same time, the optimization analysis of inner nozzle is very important to the design of a new bit.

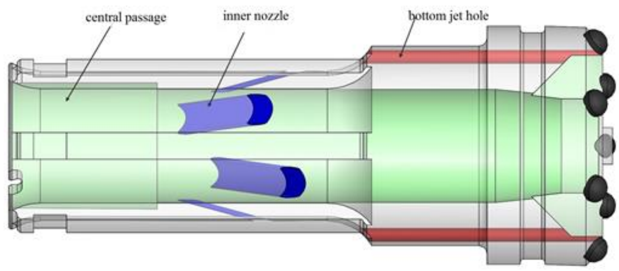
3. Design and comparative analysis of two reverse circulation bits

3.1. Design of two kinds of bits

The reverse circulation bit is the key to realize the desired effect of the reverse circulation drilling technique of the hollow-through DTH hammer (Zhang *et al*., 2007; Geng, 1995), thus two kinds of reverse circulation bits are designed as shown in Figure 2. The A-typed bit is a type of reverse circulation bit with double-row inner nozzle. By designing the inner nozzle in the bottom of the spline groove into double-row nozzle, the pumping effect to the bottom fluid of the bit can be improved, and the better reverse circulation effect can be achieved. The B-typed bit is a slit-type nozzle reverse circulation bit, and its slit-type nozzles divide the ring-shaped injection port into narrow slots with same over-flow area. High pressure fluid is injected through narrow slots into the central channel to form an upward high-speed fluid.



A. typed bit



B. typed bit

Figure 2. Geometric models of two kinds of bits

3.2. Numerical simulation analysis

On the premise of ensuring the accuracy of calculation, simplifying the fluid channel model can not only save a lot of numerical simulation time, but also achieve a targeted optimization of the inner nozzle structure to reduce the influence of disturbance factors. The simplified model is modeled using CAD software SolidWorks (Figure 3). The fluid channel model of double-row inner nozzle is meshed by Hyper Mesh grid partition software.

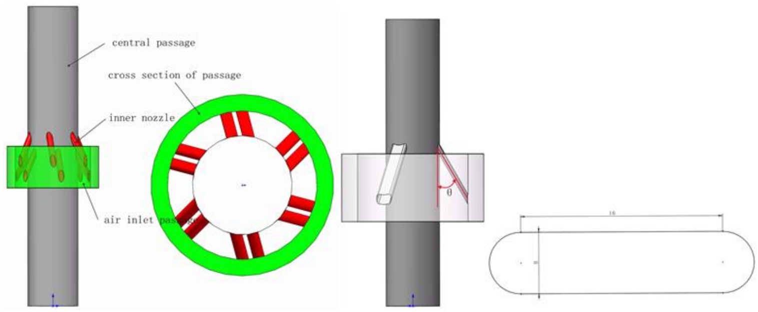


Figure 3. Three-dimensional modeling of the simplified model

This numerical simulation is for the comparative analysis of the reverse circulation structure with the double-row inner nozzle. Therefore, the same boundary conditions are ensured, and the over-flow area of the inner nozzle is ensured to be the same. The diameter of double-row inner nozzle is 7mm, and the diameter of central channel is 68mm. The width of narrow slot of slit-type nozzle structure is 3mm, and there are 6 narrow slots. The inlet of double-row inner nozzle fluid channel is configured as a mass inlet, and the upper and lower end surfaces of the center passage are configured as pressure outlets. For the mass inlet, the input air mass is set as 0.54 kg/s (about $27m^3$/min), the turbulence intensity i 3.72%, and the hydraulic diameter 30mm. For the upper end pressure outlet, the pressure is set as atmospheric pressure, the turbulence intensity 3.1%, and the hydraulic diameter 60 mm. For the lower end pressure outlet, the pressure is set as atmospheric pressure, the turbulence intensity 3.8%, and the hydraulic diameter 10 mm (Wang *et al.*, 2005).

Fluid medium air is a compressible fluid, so the ideal gas model in Fluent is used as the fluid material model, and Coupled algorithm is used as the pressure and velocity coupling calculation of the compressible fluid flow field. During the solution process, the convergence of the calculation is determined by observing the combination of the residual curve and the outlet quality curve at the upper and lower ends of the central channel. Under normal circumstances, it is considered that convergence is obtained when the residual curve is less than 10^{-6} or the flow curve at the upper and lower outlets of the central channel tends to be gentle. The M_{ring} (gas suction volume of outer ring gap) is introduced as an index of the test. By judging M_{ring} values, the pumping effect of the double-row inner nozzle structure is determining, wherein $M_{\text{ring}} > 0$ indicates that there is a pumping effect, $M_{\text{ring}} < 0$ indicates that there is no pumping effect and some gas flows to the outer ring gap, and $M_{\text{ring}} = 0$ indicates that the pumping capacity of the inner nozzle to the bottom of the nozzle is very weak. Therefore, the larger the value of the M_{ring}, the better the pumping effect, and the better the reverse circulation effect will be.

3.3. Analysis of fluent results

Figures 4 and 5 show the distribution cloud charts of the pressure field and the pressure curve in the axial direction of two kinds of inner nozzle reverse circulation structures (Hao *et al*., 2008). As can be seen from the Figures, the double-row inner nozzle structure has a high-pressure zone at the upper part of the nozzle relative to the surrounding fluid and it can also be seen in the curve that a large amplitude fluctuation occurs in this zone. It can be clearly seen that in slit-type inner nozzle structure there is a low-pressure zone at the nozzle, where the pressure gradually increases as the height increases. It can also be seen from the curve that there is a significant low pressure near 0.25m, and the pressure restores to normal pressure near 0.25m-0.36m. There are no obvious large-amplitude fluctuations appear as in the double-row inner nozzle structure.

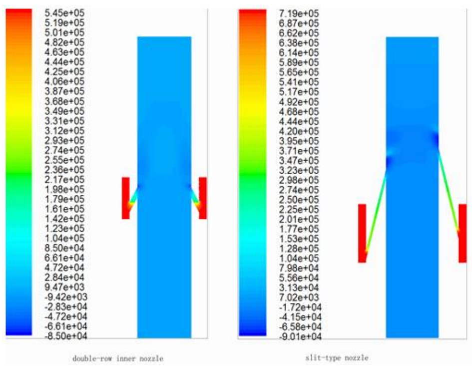


Figure 4. Pressure cloud chart of two kinds of inner nozzle structures

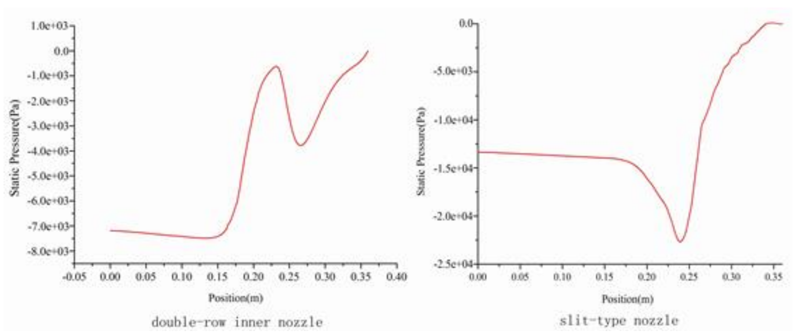


Figure 5. Pressure distribution curves of two kinds of inner nozzle structures along the central axis

Figures 6 and 7 show the speed cloud charts and the distribution of speeds in the direction of the central axis of the two kinds of inner nozzle structures, respectively. Through the analysis, it can be seen that the speed of the slit-type inner nozzle is relatively large, and that of the double-row inner nozzle is relatively small at the bottom of the central channel. In the distance from the bottom of the central channel to the inner nozzle, the fluid speed in the axial direction of inner nozzle in the ring groove gradually decreases. The speed above the nozzle begins to gradually increase, but the growth rate is slow, suggesting that the pumping time of ring groove structure is very long, which is beneficial to reverse circulation slag discharge. Both the inner nozzle and the slit-type nozzle first decline greatly and then quickly rise.

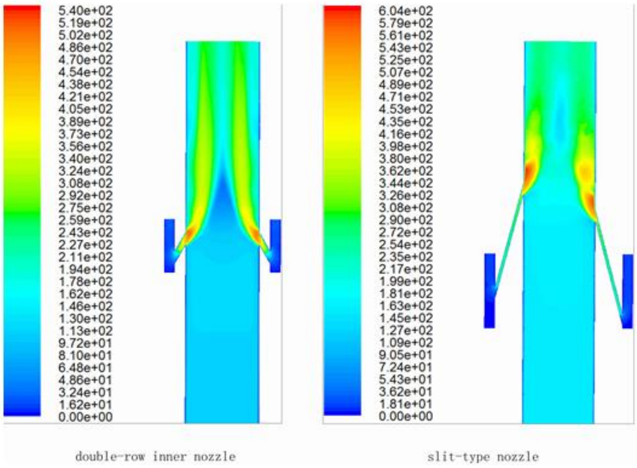


Figure 6. Speed cloud charts of two kinds of inner nozzle structure

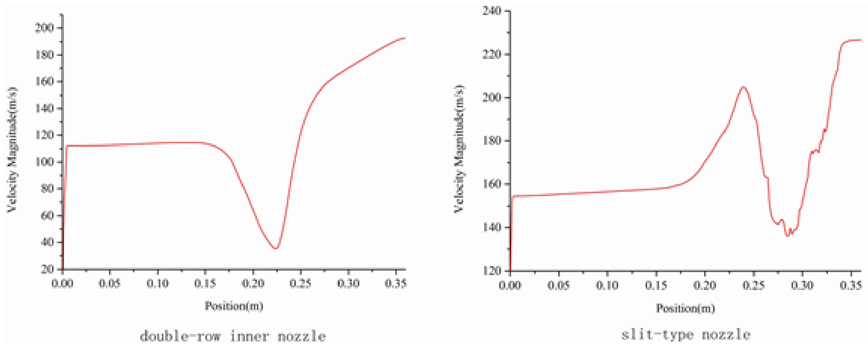


Figure 7. Speed distribution curves of two kinds of inner nozzle structures along the central axis

Figure 8 shows a pressure distribution curve in the diameter direction on the bottom cross-section. Through the analysis, it can be seen that the inner nozzles of the two different structures form a low-pressure zone at the central axis of the central channel. The minimum negative pressure at the bottom of central channel of slit-type nozzle structure is -13.35Kpa, while that of double-row nozzle structure is -7.19Kpa. The smaller negative pressure value at the bottom, the stronger pumping capability of the upper nozzle to the bottom, and the better the reverse circulation effect will be.

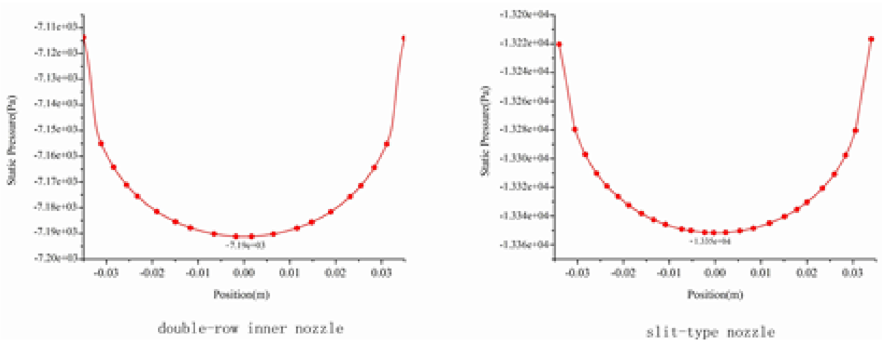


Figure 8. Pressure distribution curve on the bottom cross-section

According to the above simulation test, it can be concluded that the pumping effect of the slit-type inner nozzle structure is better. And it can be seen from the speed chart that the wall attachment effect of slit-type structure is the best, as the flow field is evenly distributed, which greatly reduces the interference effect of fluid.

4. Field test effect

According to the CFD analysis results, the optimal parameter combinations for the double-row inner nozzles are Θ_s=30°, Θ_d =10°, L=-15mm (the left nozzle is higher than the right one by 15mm) and S=10mm. This parameter combination is processed as the structural parameters of the 150mm reverse circulation bit of the double-row inner nozzle (shown in Figure 9), for which a multi-layer hollow drilling and probing productive test is conducted in the open mining area of the Lanxian County Mining Company of Taiyuan Iron and Steel Group.

The purpose of this test is to use GQ-142 hollow-through DTH hammer to connect the newly designed 150mm reverse circulation bit to cross the underground multi-layer empty area. (Zhu *et al*., 2012)

After the first hole is drilled for 0.2 meters, reverse circulation is formed, and the average drilling efficiency reaches 36m/h in the 12m loose slag layer. When drilling to 17.6m, the roof of the first empty zone is penetrated. Then, when lowering the drilling tool to 28.6m, the bottom floor of the first empty zone is reached. Pass through the hollow space of the first layer empty zone and continue to drill into the bottom floor of the first layer empty zone (Bonnington and King, 1976; Keenan and Neumann, 1950). When drilling to 44m, the roof of the second floor is penetrated. At that point, stable reverse circulation can still be formed, with good drilling effect (as shown in Figure 10). The large-grain rock blocks are continuously discharged (as shown in Figure 11), with the maximum diameter of 55mm. There is no stuck or burial of drill in the drilling process.

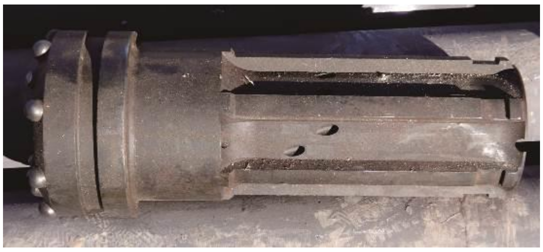


Figure 9. 150mm reverse circulation bit

Figure 10. Reverse circulation drilling effect on site

Figure 11. Large-grain rock blocks discharged from the reverse circulation

Then the second and third drilling tests are carried out in the mining area with a total footage of 43.2m and average drilling efficiency of 12.8m/h or more. The reverse circulation drilling effect is good (Tucker and Pan, 2000).

5. Conclusions

1) The test results of Lanxian County mining area show that the newly developed slit-type reverse circulation bit realizes the hollow-through DTH hammer reverse circulation drilling technique, and achieves advantages of fast drilling speed, high rock coring rate, and non-pollution at the orifice. The design of slit-type inner nozzle structure can make the reverse circulation bit obtain higher drilling efficiency and good reverse circulation effect, which is of great significance for drilling and detection of various forms (Causon *et al*., 2000; Ingram *et al*., 2003; Hartmannn *et al*., 2011).

2) Numerical simulation is used for the numerical simulation analysis of two kinds of reverse circulation bits. The results show that the structure design of slit-type reverse circulation bit is reasonable, the indexes of which all exceed those of double-row inner nozzle reverse circulation bit.

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