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Original Paper

Research on the Flow Field of the RC600 Down-the-Hole Hammer Drill Bit under Varied Bottom Shapes

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Abstract

It is of great significance to reveal the influence on the reverse circulation performance and cuttings transport efficiency of Large-diameter pneumatic DTH hammers under different bottom structures to improve their cuttings removal efficiency used in drilling applications. These findings hold significant value for improving rock carrying performance in drilling applications. Using multiphase flow numerical simulations, the effects of three different bottom structures—flat-bottom, concave-bottom, and convex-bottom—on flow field characteristics and cuttings transport efficiency were analyzed. The results indicate that the concave-bottom drill bit demonstrated the best performance in airflow concentration and cuttings suction efficiency, achieving the highest cuttings transport efficiency of 97.67%. Although the convex-bottom drill bit exhibited the highest suction ratio at 51.12%, its cuttings transport efficiency was not significantly better than the other designs. These findings provide theoretical support for the design of bottom shapes in large-diameter DTH hammers and have practical implications for enhancing drilling efficiency.

Keywords

Large-diameter down-the-hole hammer, Flow field characteristics, Rock debris transport efficiency, CFD numerical simulation

1. Introduction

The development and utilization of mineral resources are fundamental to societal progress, yet accidents such as collapses, explosions, and water inrush occasionally occur during underground mining, particularly in metal and non-metallic ore deposits. These incidents pose significant threats to miners' safety. In 2023 alone, China reported five major coal mine accidents, resulting in 76 fatalities and 51 injuries, alongside one catastrophic accident with 53 fatalities. The safety production situation remains critical.

In the aftermath of mining disasters, rapid establishment of escape routes to improve survival rates of trapped individuals is paramount. Large-diameter pneumatic DTH hammer drilling technology, known for its high drilling speed, low cost, and excellent borehole quality, has been widely applied in rescue drilling operations. For example, during the 2010 San José copper mine collapse in Chile, rescue teams successfully utilized large-diameter DTH hammer drilling to save 33 miners in 69 days. Similarly, in the 2015 gypsum mine collapse in Pingyi County, Shandong Province, the technology was employed to rescue four miners in 36 days. This marked the first successful use of the technology for mine rescue in China, a milestone in the country's mining rescue history. Despite its successful applications, feedback from field operations indicates that large-diameter DTH hammers still lack sufficient theoretical underpinnings, presenting challenges in trajectory control and cuttings removal during emergency rescue applications.

Conventional positive circulation drilling methods often fall short in rescue scenarios due to large borehole diameters, stringent wellbore trajectory control requirements, complex geological conditions, and the presence of void zones. To address these issues, large-diameter reverse circulation DTH hammer drilling technology has emerged as the optimal solution. It improves cuttings transport, reduces lost circulation in fractured formations, lowers surface equipment requirements, and minimizes auxiliary time for drill string removal.

Significant progress has been made in the design and development of large-diameter reverse circulation DTH hammers. Jilin University successfully developed two specifications of through-passage reverse circulation DTH hammers with diameters of Φ400 mm and Φ660 mm. The Xi’an Research Institute of China Coal Technology & Engineering Group also contributed important innovations, including the Φ660 mm bundled reverse circulation DTH hammer and the Φ710/311 mm reaming bundled reverse circulation DTH hammer. These designs optimize cuttings removal through bundled structures, improve drilling speed, and adapt to various borehole diameters for efficient drilling.

Internationally, NUMA’s Champion330 pneumatic DTH hammer achieves a drilling diameter of 1092 mm. Ingersoll-Rand's CD series modular DTH hammers are designed for large-diameter drilling, and Ireland’s MINCON company developed high-performance reverse circulation drill bits in 2006 with a drilling diameter of 1092 mm. Domestically, the J-200 pneumatic DTH hammer achieved a cumulative drilling length of 11,000 meters, marking the earliest use of large-diameter DTH hammers in China. In 1987, Jilin University successfully developed the FGC-15 and FGC-15B reverse circulation DTH hammers with diameters ranging from 600 to 1200 mm, applied in subsea rock anchoring and grouting pile construction. Wang Maosen et al. investigated ring-type combination DTH hammer drilling technologies, designing and optimizing the HC-15 hammer, significantly reducing manufacturing costs, operational difficulty, and improving efficiency. Yang Hongwei highlighted the advantages of air-lift reverse circulation technology in large-diameter construction, demonstrating increased drilling efficiency and notable economic benefits.

In recent years, researchers have employed CFD analysis to study DTH hammer performance. Zhang Xinxin et al. (2019) analyzed internal flow and impact performance, concluding that increasing rebound coefficients and input air pressure enhanced impact efficiency, while higher piston mass reduced performance. In 2024, Shi Yuanling of Jilin University designed four drill bits tailored to different drilling conditions, with CFD simulations identifying structural parameters conducive to efficient reverse circulation and geological adaptability.

Among various large-diameter DTH hammers, pneumatic reverse circulation models are widely utilized due to their unique working principles and numerous advantages. By integrating inner jet holes based on the ejector principle, high-speed airflow generates a low-pressure region below the central channel, inducing reverse circulation without the need for sealing devices or drilling fluid. This design offers minimal formation constraints, high cuttings removal efficiency, and excellent borehole cleanliness. Additionally, the bottom shape of the drill bit significantly affects borehole cleanliness. An optimized bottom design effectively clears rock cuttings, reduces clogging, and ensures continuous and efficient drilling.

While small-diameter pneumatic reverse circulation DTH hammers have reached maturity, their theories and designs cannot be fully applied to large-diameter models. Research on large-diameter DTH hammer structures remains limited, with challenges such as low cuttings removal efficiency persisting. To investigate the influence of drill bit bottom shapes on reverse circulation performance, this study proposes three bottom structure designs for a 600 mm diameter reverse circulation DTH hammer. Numerical simulation software is used to analyze the flow field of each design, aiming to identify the optimal structure. Comparing the simulation results provides deeper insights into the impact of bottom shapes on reverse circulation performance, offering guidance for future large-diameter pneumatic reverse circulation DTH hammer design.

Given the time-consuming and costly nature of traditional experiments, which often require multiple sets under varying conditions, Computational Fluid Dynamics (CFD) has become an essential tool. CFD simulation offers advantages such as low cost, fast computation, and the ability to model diverse working conditions. In recent years, CFD has evolved into a key technology in fluid mechanics research. This study employs CFD to analyze the three drill bit models, identifying design parameters to enhance the performance of large-diameter pneumatic reverse circulation DTH hammers.

2. Numerical Simulation of Gas-Solid Two-Phase Flow in Large-Diameter Pneumatic Reverse Circulation DTH Hammer Drill Bit

2.1 DTH Hammer Bit Model Design

To ensure the drill bit effectively establishes reverse circulation and achieves efficient cuttings removal, the drill bit utilizes the ejector principle by designing inner jet holes at the central channel. Airflow enters the drill bit through the gap between the splines and the spline sleeve, then flows toward the inner jet holes and bottom jet holes. High-speed airflow converges near the inner jet holes in the central channel, creating a low-pressure region below, which facilitates the formation of reverse circulation. The bottom jet holes serve two main purposes: first, to cool the tungsten carbide inserts embedded in the drill bit; second, to sufficiently agitate the rock cuttings at the borehole bottom, thereby achieving improved cuttings removal efficiency.

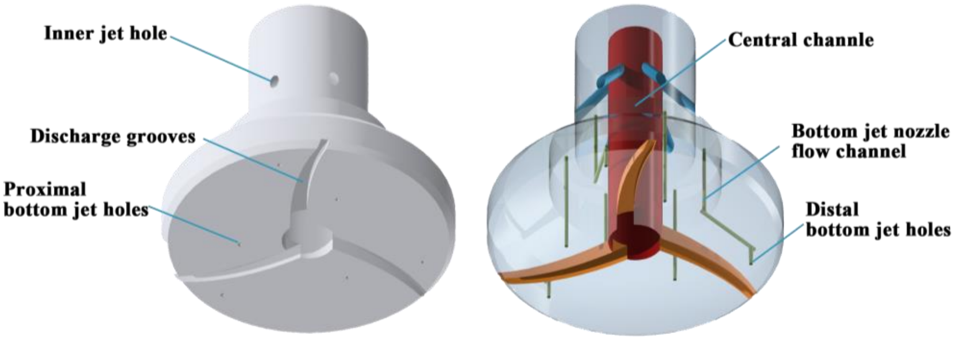


Figure 1. Perspective View of the Bit's Overall and Internal Structure

The drill bit is designed with six inner jet holes and six bottom jet holes to enhance the removal efficiency of rock cuttings from the borehole bottom, as shown in Figure 1. To further improve the cuttings removal efficiency and prevent localized accumulation of rock cuttings at the borehole bottom, the bottom jet holes and three discharge grooves of the drill bit were redesigned.

This study investigates the influence of drill bit bottom shapes on reverse circulation performance. Three bottom shape designs were proposed, as shown in Figure 2: concave, flat, and convex. For the drill bit model, non-essential geometric features were simplified to conserve computational resources while preserving key characteristics and physical properties of the model. Other reverse circulation structural parameters are listed in Table 1.

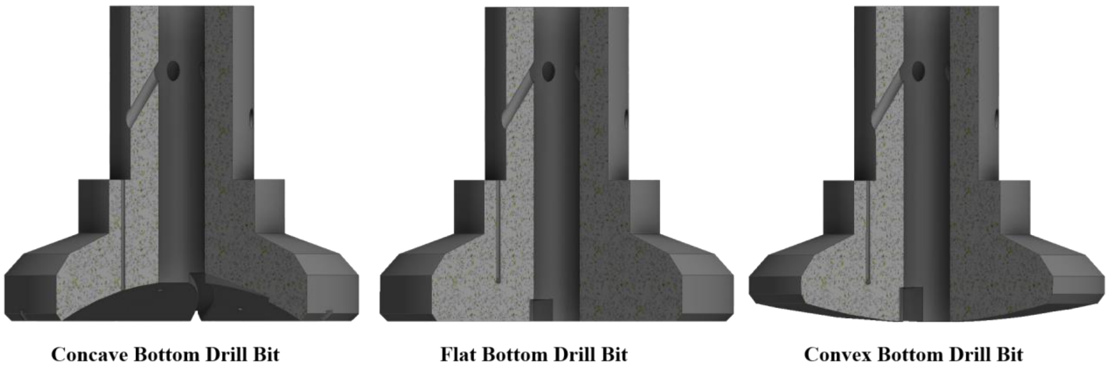


Figure 2. Three-Quarter Section Views of Bits with Three Different Bottom Structures

Table 1. Structural Parameters

Name	Value	Unit
Inner jet hole Diameter	22	mm
Inner jet hole Angle	40	deg
Bottom jet hole Diameter	8	mm
Central channle Diameter	110	mm

The drill bit and borehole models were imported into DesignModeler for flow channel extraction, as shown in Figure 3a. Subsequently, Fluent Meshing was used to generate polyhedral meshes. During mesh generation on the simplified model, coarser meshes were applied to regions with minimal influence on flow characteristics, while finer meshes were employed in areas with significant impact, such as the inner jet hole region and near the discharge grooves. This approach ensured the accuracy of the flow field simulation. The total number of mesh elements was controlled at approximately 1 million. The specific mesh generation and the half-sectional view of the fluid domain mesh elements are illustrated in Figure 3b.

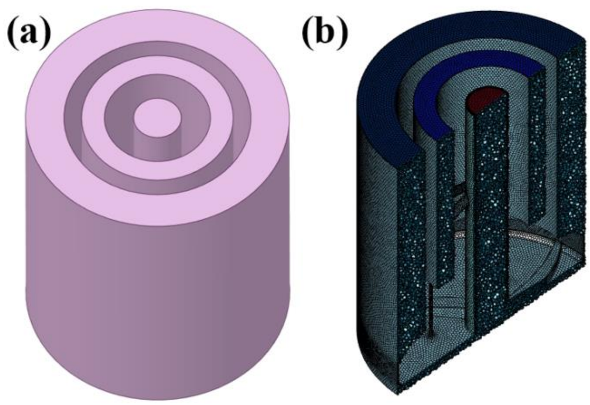


Figure 3. Fluid Domain and Mesh Cell Section View

This paper will employ the DPM (Discrete Phase Model) in Fluent for numerical simulation of gas-solid two-phase flow. The turbulence model selected is the k-ε RNG (Re-Normalization Group) turbulence model, along with enhanced wall functions. The pressure-based solver is chosen, and the gas model utilizes the ideal gas model, taking into account the effects of gravity on the flow field. Boundary condition parameters are set under the working conditions of a mechanical drilling speed of 2m/h and an air supply rate of 60m³/min. The specific types of boundary conditions and their values are shown in Table 2.

Table 2. Boundary Condition Parameters

Name	Boundary Condition Type	Value
Inlet	Mass flow inlet	1.224Kg/s
Outlet	Pressure outlet	-
Particle_inlet	Wall	0.402Kg/s
Annular space	Pressure outlet	-

2.2 Evaluation Metrics for Reverse Circulation Performance

The working principle of reverse circulation reaming drill bits reveals two primary sources of gas supply within the drill tool. The first source is the fixed gas input provided directly by the air compressor, and the second is the natural suction of gas from the annular space between the borehole wall and the drill bit. Simultaneously, rock cuttings inside the drill tool are primarily generated by the cutting action of carbide inserts at the borehole bottom. These cuttings are then carried by the airflow into the suction ports and ultimately discharged through the central channel.

This study introduces two key parameters to evaluate drill bit performance: suction ratio and cuttings transport efficiency.

The suction ratio is defined as the ratio of the total mass flow rate of gas drawn from the annular space between the borehole wall and the guide column, combined with the mass flow rate of gas drawn through the guide holes, to the mass flow rate of gas output by the air compressor.

Cuttings transport efficiency is defined as the ratio of the discharge rate of rock cuttings from the drill bit to the generation rate of rock cuttings at the borehole bottom.

These parameters provide a quantitative basis for assessing the operational efficiency and effectiveness of reverse circulation drill bits.

This paper conducts multiple flow simulations under the same conditions for models with different bit bottom structures, aiming to reveal the impact of different bit structures on flow field changes and the reasons behind them. The discussion in this paper will focus on the simulation results of the flow field and particles.

3. Numerical Simulation Results and Analysis

This study conducted two-phase flow simulations under identical working conditions for models with different drill bit bottom structures. The aim was to reveal the impact of various drill bit designs on flow field variations and the underlying causes. The discussion will focus on the simulation results of the flow field and particle behavior in combination.

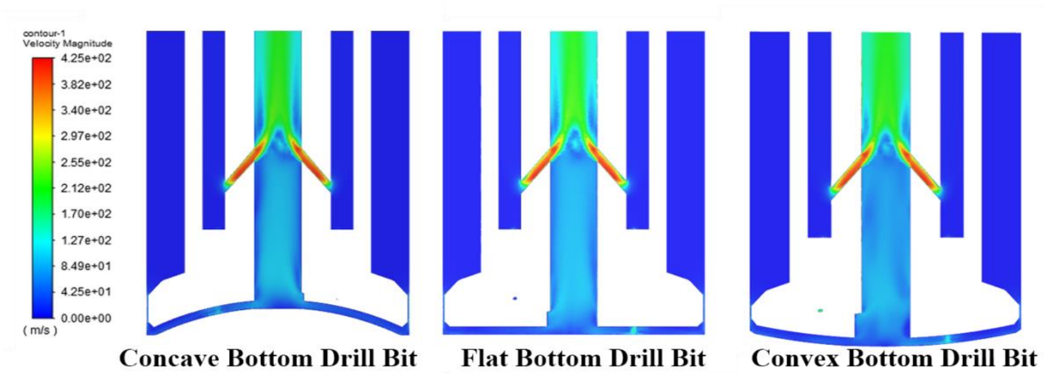


Figure 4. Internal Cross-Sectional Velocity Cloud Maps under Different Bit Bottom Structures

After the flow stabilized, the velocity distribution within the flow field was analyzed. Figure 4 presents the velocity contour plots of airflow within the drill bit cross-section for different bottom structures. Observing the images reveals that under the influence of high-speed airflow from the inner jet holes, the airflow velocity near the inner jet holes reaches the global peak for all drill bit designs, with a maximum velocity of up to 425 m/s. The maximum velocity differences among the three designs are minimal, with a variance of only 1.03%.

However, examining the velocity distribution below the inner jet holes reveals distinct differences in flow patterns for the three bottom designs. For the concave-bottom drill bit, high-speed airflow is predominantly concentrated at the center of the drill bit. In contrast, the flat-bottom and convex-bottom drill bits exhibit a more uniform radial velocity distribution. The axial-to-boundary velocity difference for these two designs is significantly smaller compared to the concave-bottom drill bit with three different structural shapes. For the concave-bottom bit, high-speed airflow is generally concentrated at the center of the bit, a phenomenon not observed in the other two types of bit structures.

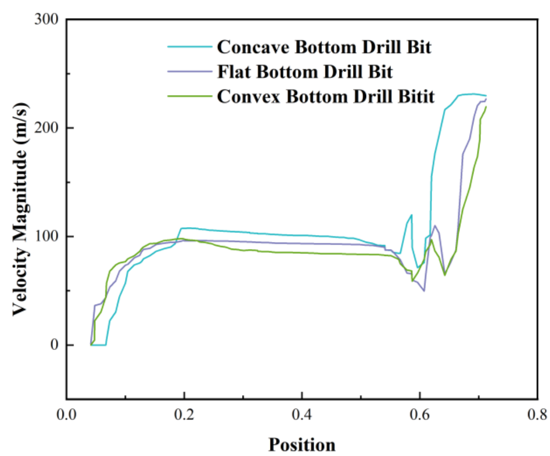


Figure 5. Axial Air Velocity Distribution in Central Passage for Different Bit Bottoms

Figure 5 shows the axial velocity distribution curves of airflow in the central channel for different drill bit bottom shapes. According to the data presented, the concave-bottom drill bit achieves an airflow velocity of 225.3 m/s at 0.73 m along the central channel, making it the first among the three designs to reach velocity stabilization. Additionally, all three drill bits exhibit a sudden velocity change near 0.6 m along the central channel, followed by recovery. This phenomenon is caused by the convergence of high-speed airflow from the inner jet holes along the channel axis.

The concave-bottom drill bit maintains higher airflow velocities below the inner jet holes in the central channel compared to the other two designs, with an average velocity of 104.5 m/s, which is up to 15.78% higher than the maximum values of the other designs. This higher velocity is advantageous for the discharge of rock cuttings. The reason lies in the airflow direction at the borehole bottom: for the concave-bottom drill bit, the angle between the bottom airflow direction and the upward velocity in the central channel is acute, minimizing velocity loss. In contrast, the flat-bottom and convex-bottom drill bits have right or obtuse angles, resulting in greater velocity loss.

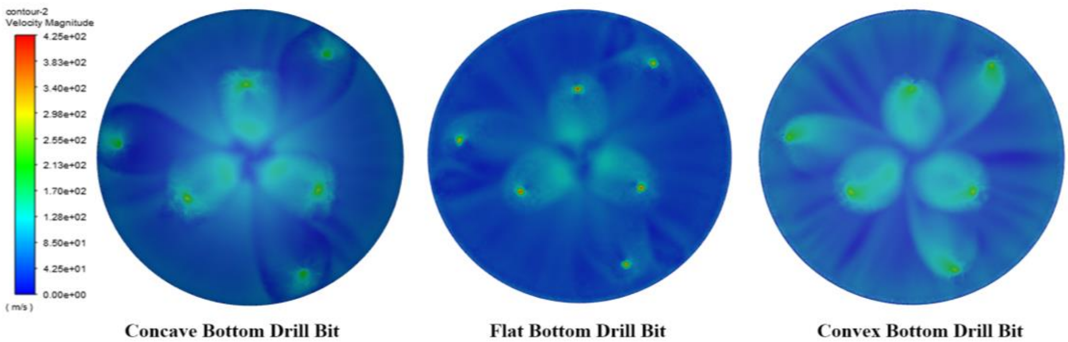
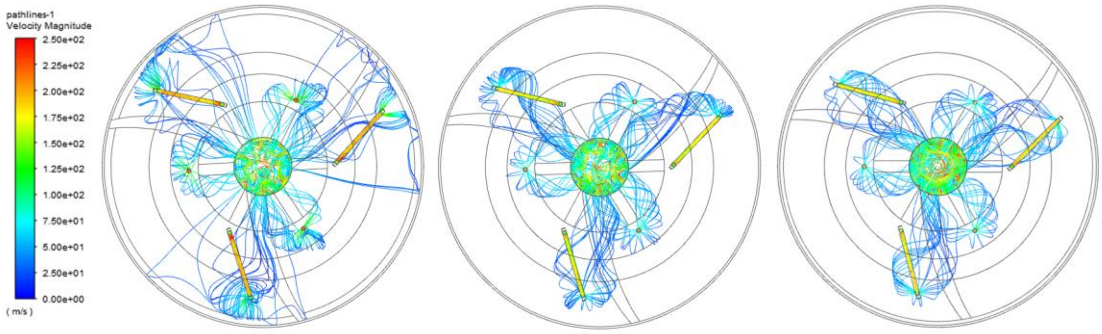


Figure 6. Bottom Flow Field Velocity Maps for Different Bit Bottoms

As shown in Figure 6, the velocity distribution cloud map of the bottom hole gas for different bit bottom structures reveals that the flat-bottom bit has the highest gas velocity at the bottom nozzle position, reaching 236 m/s. This is because the bottom of the flat-bottom bit is also flat, resulting in a uniform distribution of rock cuttings, and the gas encounters the least resistance, thus achieving the maximum velocity among the three structures. The other two bit structures tend to accumulate cuttings at the bottom due to gravity and air flow, leading to a loss in gas velocity.

Additionally, observing the flow field near the three bottom nozzles closest to the central passage, the concave-bottom bit has the highest average gas velocity, at 57.21 m/s, followed by the convex-bottom bit at 50.23m/s, while the flat-bottom bit has the lowest average gas velocity at 47.68 m/s in this area. The concave-bottom bit has the highest average gas velocity near the bottom nozzles because the concave structure concentrates the air flow at the bottom of the bit, reducing dispersion and resulting in higher gas velocities near the bottom nozzles. This high-velocity air flow is beneficial for more effectively removing cuttings and reducing their accumulation at the bit bottom.



Concave Bottom Drill Bit **Flat Bottom Drill Bit** **Convex Bottom Drill Bit**

Figure 7. Streamline Plots of Air Velocity for Different Drill Bit Structures

From the streamline plot, the flow direction and trajectory of the fluid can be clearly observed, aiding in the identification of fluid behavior. To better understand the gas flow direction and influence range at the borehole bottom, gas velocity streamlines were established with the bottom jet hole as the starting point, as shown in Figure 7. It is evident that the gas ejected from the bottom jet hole under the concave-bottom drill bit exhibits the largest influence range. The streamlines at the drill bit bottom are more dispersed, with part of the fluid being directed toward the outer edge region, whereas the influence range of the bottom jet hole for the other two drill bit structures is largely the same.

By observing the streamlines near the cuttings discharge grooves, it is apparent that for both the flat-bottom and convex-bottom drill bits, most of the gas flows through the discharge grooves into the central channel. This phenomenon is likely due to the accumulation of rock cuttings, which forces the gas to enter the central channel through the larger space provided by the discharge grooves. This indirectly suggests that these two drill bit designs may lead to particle accumulation at the borehole bottom.

Table 3. Suction Ratio and Cuttings Transport Efficiency

Parameter Name	Convex Bottom Drill Bit	Flat Bottom Drill Bit	Concave Bottom Drill Bit
Suction Ratio	47.54%	48.59%	51.12%
Cuttings Transport Efficiency	97.67%	93.52%	95.23%

Table 3 presents the suction ratio and cuttings transport efficiency for bits with three different bottom structures. The convex-bottom bit has the highest suction ratio, while the concave-bottom and flat-bottom bits have a suction ratio that differs by only 1.05%. The concave-bottom bit has the highest cuttings transport efficiency, and the flat-bottom bit has the lowest, with the highest difference in cuttings transport efficiency being 4.15%. The convex-bottom bit has the highest suction ratio because the convex structure forms an area at the bottom of the bit that is more conducive to the formation of gas reverse circulation, causing the airflow at the bottom of the bit to be more dispersed, thereby increasing the suction ratio. However, this design may lead to local accumulation of cuttings at the bottom of the bit, resulting in a loss of gas velocity in the central passage, which in turn affects the cuttings transport efficiency. It can be seen that in large-diameter drilling operations, the shape of the bit bottom has a certain impact on the bit's suction ratio. Further analysis of the distribution of cuttings particles and their transport velocity within the flow field is needed to determine the causes of these differences and the impact of each bit on the transport process of cuttings particles.

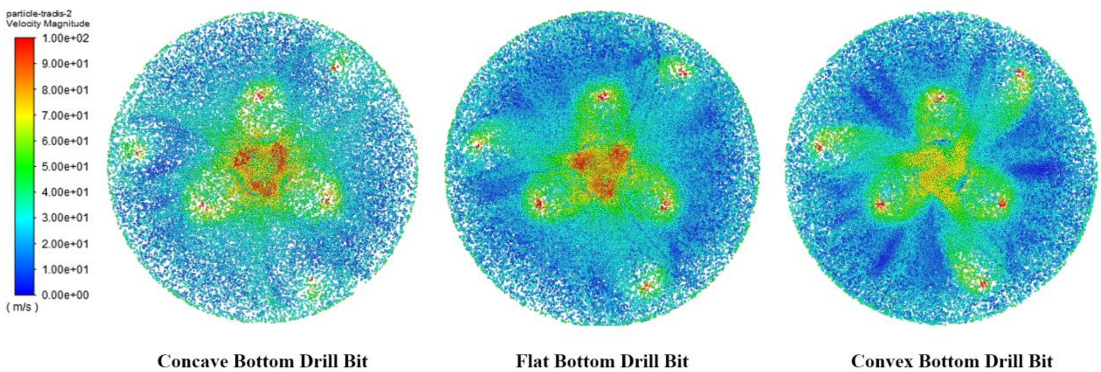


Figure 8. Particle Velocity at Hole Bottom for Different Bit Bottoms

Figure 8 clearly shows that the bottom hole cuttings distribution is the sparsest with the concave-bottom bit design, which indirectly indicates that this design has a high cleaning efficiency at the bottom of the hole, with cuttings spending less time at the bottom. Observing the velocity distribution of the bottom hole cuttings for these three types of bits, it can be seen that the convex-bottom bit has the highest number of slow-moving cuttings among the three. Cuttings with a velocity less than 2 m/s account for 43.23% of all bottom hole cuttings, while for the concave-bottom bit, cuttings with a velocity less than 2 m/s account for 35.07% of the total number of cuttings, and the amount of cuttings at the bottom of the hole for the concave bit is only half that of the convex bit.

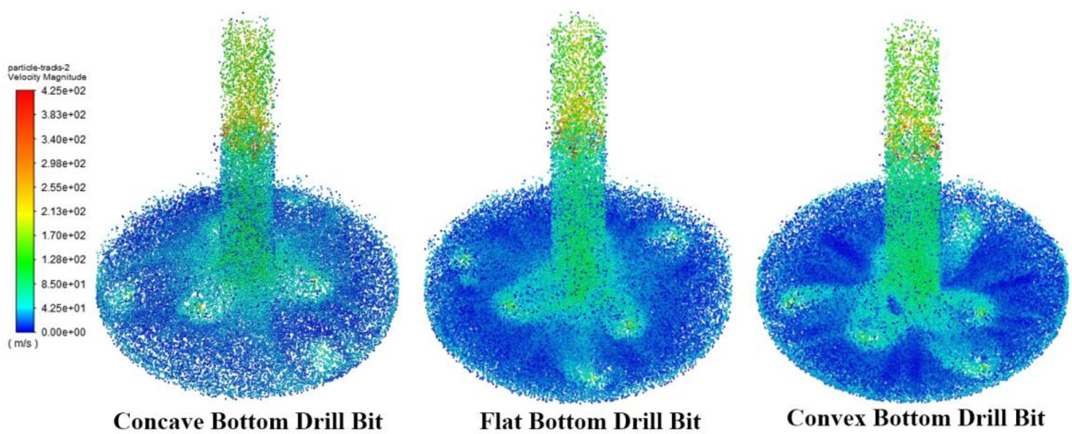


Figure 9. Particle Velocity Distribution in the Flow Domain

As shown in Figure 9, the velocity distribution of particles within the flow field and their spatial distribution are illustrated. The figure depicts the entire process of particles being generated at the borehole bottom and subsequently accelerated through the central channel. The concave drill bit exhibits the highest average particle velocity at 93.76 m/s, followed by the flat-bottom drill bit at 87.32 m/s, while the convex drill bit demonstrates the lowest average particle velocity at 80.23 m/s, which is 14.43% lower than that of the concave drill bit. These results indicate that the concave drill bit achieves superior borehole bottom cleaning performance, effectively agitating rock cuttings at the bottom and maximizing cuttings transportation efficiency.

The higher average particle velocity observed in the concave drill bit can be attributed to its structural design. Specifically, the upward-convex shape of the borehole bottom facilitates the airflow in lifting particles along the borehole bottom, enhancing particle suspension. Furthermore, during the migration of rock cuttings toward the central channel, particles experience an acceleration process. This acceleration can be decomposed into components opposite to gravity and perpendicular to gravity, enabling particles beneath the central channel to reach the highest velocity. The velocity vector also includes a component opposing gravity, allowing particles to enter the central channel with an increased upward velocity, thereby enhancing cuttings removal.

In summary, the design of the drill bit bottom structure significantly influences the reverse circulation efficiency of the flow field and the efficiency of cuttings transportation. The concave drill bit, with a bottom structure conducive to airflow concentration and effective cuttings removal, demonstrates the highest transportation efficiency. Although the flat-bottom drill bit achieves higher airflow velocity near the bottom jets, its transportation efficiency is limited by the accumulation of cuttings beneath the central channel. The convex drill bit, despite its higher suction potential, does not exhibit significantly improved transportation efficiency due to localized cuttings accumulation caused by its bottom structure.

4. Results and Discussion

Through numerical simulations of three different bottom structure designs for a 600 mm diameter reverse circulation down-the-hole (DTH) hammer, this study analyzed the flow field and the behavior of rock cuttings within the borehole. The influence of drill bit bottom shapes on reverse circulation performance and cuttings transport efficiency was thoroughly examined, leading to the following conclusions:

(1) The drill bit bottom structure significantly affects velocity distribution and airflow stability within the flow field. The concave-bottom drill bit concentrates high-speed airflow near the inner jet holes at the drill bit center, enhancing cuttings suction efficiency, reducing rock cuttings accumulation at the borehole bottom, and improving debris removal. Furthermore, the concave-bottom drill bit achieves a velocity of 225.3 m/s at 0.73 m along the central channel, reaching stabilization earlier than the other two designs. This advantage in airflow stability is crucial for improving drilling efficiency.

(2) The bottom structure directly impacts the efficiency of cuttings transport. The concave-bottom drill bit demonstrates the highest cuttings transport efficiency, while the flat-bottom drill bit performs the worst. Sparse distribution of rock cuttings at the borehole bottom with the concave-bottom drill bit indicates higher cleaning rates and shorter residence times for cuttings. Additionally, particles transported through the central channel exhibit the highest average velocity for the concave-bottom drill bit, while the convex-bottom drill bit shows the lowest. These findings highlight the superior cleaning effect of the concave-bottom design, which more effectively agitates and removes rock cuttings from the borehole bottom.

(3) The convex-bottom drill bit exhibits the highest suction ratio, likely due to its structural design creating a region beneath the drill bit bottom that is more conducive to reverse circulation airflow. This results in more dispersed airflow at the drill bit bottom and an increased suction ratio. However, this design leads to localized accumulation of rock cuttings at the drill bit bottom, negatively affecting cuttings transport efficiency.

In summary, the bottom structure of a drill bit significantly influences its reverse circulation performance and cuttings transport efficiency. The concave-bottom drill bit, with its design favoring airflow concentration and efficient rock cuttings removal, demonstrates superior performance. These findings provide valuable insights and reference points for the design of large-diameter pneumatic reverse circulation DTH hammers in the future.

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