

## Research Article

# Experimental and Numerical Study on Air Flow Behavior for a Novel Retractable Reverse Circulation Drill Bit of Casing-while-Drilling (CwD)

Bo Qi <sup>1,2</sup>, Pinlu Cao <sup>1</sup>, He Yang <sup>1</sup>, Wenbo He <sup>1</sup>, Mengke Wang <sup>1</sup>, Baoyi Chen,<sup>1</sup>  
Kun Bo <sup>1</sup> and Zhichuan Zheng <sup>1</sup>

<sup>1</sup>College of Construction Engineering, Jilin University, No. 938 Ximinzhu Str., Changchun City 130061, China

<sup>2</sup>Changchun Institute of Technology, No. 395 Kuanping Str., Changchun City 130012, China

Correspondence should be addressed to Zhichuan Zheng; zhengzc@jlu.edu.cn

Received 30 June 2021; Accepted 31 July 2021; Published 21 August 2021

Academic Editor: José Luis Pastor

Copyright © 2021 Bo Qi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

A reverse circulation Down-The-Hole (DTH) hammer drill bit in Casing-while-Drilling (CwD) processes is designed and applied to drilling under complicated formation. The drill bit is a special retractable drill bit with an exclusive reverse circulation gas channel. Using numerical simulations and experiments, the influence of the gas channel structure parameters of the drill bit, including the inner jet nozzles, flushing nozzles, suction channel, and other parameters, on its reverse circulation performance is analyzed, and the optimal gas channel structure parameters of the drill bit are determined to improve the reverse circulation effect. The results show that the flushing nozzles and inner jet nozzles have an important influence on entrainment performance. The entrainment rate  $\eta$  decreases as the flushing nozzle diameter increases and decreases as the inner jet nozzle diameter increases. An increase in the suction channel diameter can improve the reverse circulation effect of the drill bit. The spiral slot drill bit is more conducive to air being sucked into the central channel in the form of spiral flow, so it can improve the entrainment performance. The entrainment rate  $\eta$  can reach 23.4% with the optimum structured drill bit.

## 1. Introduction

Under complicated formations, wellbore instability is often accompanied by many kinds of borehole accidents, which cause economic losses and waste time. Examples include wellbore collapses, lost circulation, tight holes, and other accidents. For drilling in loose overburden with a shallow hole depth, the casing can be used to protect the hole wall. For a deep hole with a fracture zone, it is challenging to press casing into the hole. Special drilling fluid with plugging materials can be used to prevent lost circulation, as discussed elsewhere [1, 2]. However, this method is far from being able to meet the plugging requirements for flushing fluid when drilling with extremely broken formations. Injecting cement mortar into a hole to strengthen the formation is another existing solution, as discussed elsewhere [3–7]. However, this method is very difficult to operate. Improper operation will damage the borehole. A reasonable accident treatment

method is essential for drilling. With the development of Down-The-Hole (DTH) drilling technology, a DTH hammer with CwD is proposed to solve the problem of drilling under complicated formation and special environmental conditions, as discussed elsewhere [8, 9]. This special drilling method has the advantages of improved drilling speed, efficiency, and hole wall stability. The casing connected to the drill bit will be brought into the hole to protect the wall of the hole while drilling. Thus, the key to this technology is an appropriate drill bit.

Generally, the drill bit consists of a pilot bit and an expanding bit. The pilot bit is used to drill a small hole first, and then, a hole larger than the casing is completed using the expanding bit. Then, the casing can be gradually inserted into the hole, as discussed by Warren et al. [10]. For shallow boreholes, a simple and efficient method, which involves adding a ring bit in front of the casing, is used for the drilling process. While the guide bit is drilling, the ring bit can drill

synchronously. In this way, the casing can be brought directly into the hole. However, the most significant disadvantage of this method is that the drilling must be completed before the ring bit is worn and damaged because the ring bit cannot be replaced. For this reason, the application of this type of drilling method is limited by the borehole depth.

In order to drill a deep borehole, the drill bit must be replaced after reaching its service life. This requires that the drill bit be freely removed from the well through the inside of the casing tubes at any desired time. However, as mentioned above, drilling with a casing also requires the drill bit to drill a hole with a diameter larger than the casing in the well. In order to meet these requirements, a drill bit must have the ability to change its diameter freely through a specific operation. That is, the drill bit can drill a hole larger than the casing during drilling. At the end of drilling or when the bit needs to be replaced, the diameter of the drill bit can be reduced to less than the diameter of the casing, and then, the drill bit can be removed from the well. At present, there are some types of retractable drill bits used in production practice. Generally, the conventional retractable drill bit has retractable parts, which are opened by rotation or pressure. It should be noted that the cuttings from the drilling operation easily enter into the small clearance where these retractable parts are located and then lead to difficulties in closing these retractable parts. Furthermore, these parts often rely on the shaft to rotate, which results in poor force transfer performance, as discussed elsewhere [11, 12]. In addition, the air, which is carried with the rock cuttings, circulates to the surface through the annular space between the drill string and the casing. This process requires a large amount of air input, especially for large diameter boreholes. As the air circulates, there will be some air leakage along with the fractures of the formation at the bottom of the hole, so the problem of lost circulation is inevitable. Especially in complicated formations, seriously lost circulation may cause significant accidents since the cuttings cannot be cleaned effectively at the bottom of the borehole, as discussed by Cao et al. [13].

In order to avoid the failure of the retractable parts of the drill bit caused by complicated formation conditions, the drill bit has higher requirements for motion system and conductive force system. In addition, DTH hammer air reverse circulation drilling technology is an option to solve the abovementioned problems of the existing complicated formation drilling system, as discussed by Luo et al. [14]. The main characteristic of this technology is that the air fluid is circulated using reverse circulation. Compressed air coming from an air compressor flows into the hollow DTH hammer through an annular space in the double-wall drill string and powers it; it then enters into a special drill bit. After entraining the cuttings at the borehole bottom, the air moves into the central passage of the drill bit and then flows upward to the surface. Because compressed air always circulates inside drill tools, this method can effectively address problems of circulation loss in unconsolidated formations, as discussed elsewhere [15, 16]. The risk of bit blockage is also greatly reduced due to the system's excellent cutting-carrying capacity. This can ensure that the drill bit expands and contracts freely at any time. Furthermore, this method does not need

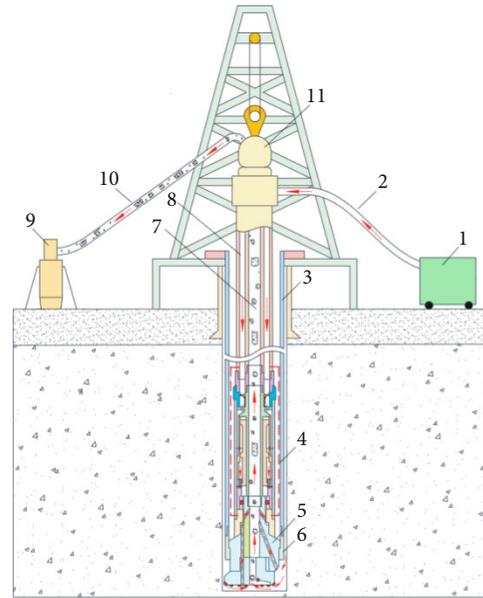


FIGURE 1: Drilling system using DTH hammer with air reverse circulation. 1: air compressor; 2: air inlet hose; 3: casing; 4: DTH hammer; 5: drill bit with reverse air circulation; 6: casing shoe; 7: central passage of dual-wall drill pipes; 8: annular space of dual-wall drill pipes; 9: cyclone separator; 10: discharge hose; 11: swivel with double channels.

to seal the top end of the casing tube since no gas can be released from it. The casing connection is also more convenient, which results in significant time savings. This paper introduces a new type of retractable DTH hammer drill bit of CwD that can form strong reverse circulation. Using numerical simulation and experimental research, the influence of the gas channel structure parameters of the drill bit, including the influence of the inner jet nozzles, flushing nozzles, suction channel, and other parameters, on its reverse circulation performance is analyzed, and the optimal gas channel structure parameters of the drill bit are determined to improve the reverse circulation effect. The conclusion is helpful for designing and application of the reverse circulation DTH hammer drill bit of CwD.

## 2. Design of a Retractable Reverse Circulation DTH Hammer Drill Bit of Casing-while-Drilling

The general concept of a new type of CwD system with a reverse circulation DTH hammer is proposed (see Figure 1), as discussed by Timonin et al. [17]. Compressed air from an air compressor flows into the annular space of the dual-wall drill pipe through the double-channel swivel and then enters the DTH hammer and drives it to impact the drill bit. The high-impact energy will be transferred to the rock through the drill bit, as discussed by Ravi et al. [18]. While drilling, a part of the impact energy will be transferred to the casing through the casing shoe and then push the casing into the well. The air is exhausted from the DTH hammer and flows through a special gas channel. Part of

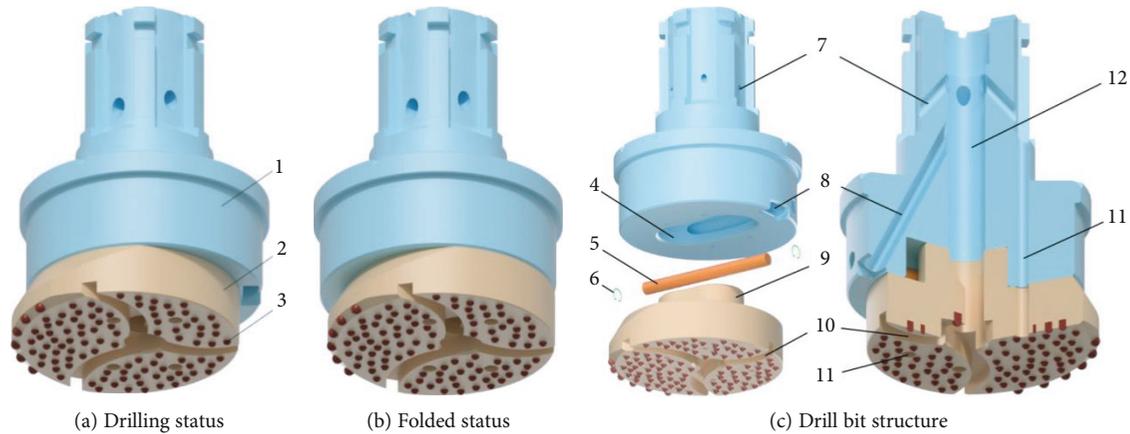


FIGURE 2: Geometric models of the retractable drill bit. 1: upper drill bit body; 2: lower drill bit; 3: carbide inserts; 4: kidney-shaped groove; 5: pin shaft; 6: snap rings; 7: inner jet nozzles; 8: suction channel; 9: kidney-shaped axis; 10: spiral slots; 11: flushing nozzles; 12: central channel.

the air reverses into the central channel of the drill bit in the form of a high-speed jet. The negative pressure produced by the jet will produce strong suction performance. Another part of the air will flow into the bottom of the borehole to cool the tungsten carbide inserts and carry the cuttings into the central channel. The air and cuttings flowing into the drill bit will be further mixed and travel upward together until they are sucked into the cyclone for further processing. While drilling is completed, the diameter of the drill bit can be reduced to less than the diameter of the casing by controlling the retractable bit, and then, all the drilling systems can be removed from the casing. Since the compressed air is subject to reverse circulation, it is pumped into the central channel at the bottom of the hole, so there is no air escaping into the surrounding formation. Moreover, the risk of a drill bit becoming clogged by rock cuttings is greatly reduced. This drilling system has low air demand. Furthermore, the high-efficiency reverse circulation improves the cleaning effect. Hence, this drilling system has substantial advantages in complicated formation drilling.

The reverse circulation drill bit has a special gas channel structure. However, in general, DTH hammer drilling has difficulty adopting reverse circulation technology for conventional casing following bits. Therefore, the key to designing this new drilling system is to design a reliable drill bit that not only needs to have a good cutting bearing capacity but also needs to be able to expand and contract freely at any time and form strong air reverse circulation so as to prevent annular air leakage between the casing and wellbore, as discussed elsewhere [19–21].

**2.1. Design Structure of the Retractable Reverse Circulation Drill Bit.** Figure 2 shows the general structure of the retractable drill bit with reverse air circulation. The utility model is mainly composed of five parts: an upper drill bit body, a lower drill bit, a pin shaft, two snap rings, and a cemented carbide blade installed at the bottom of the lower drill bit body. Six inner jet nozzles are uniformly distributed along the circumference on the upper drill bit, and the angle between the axis and vertical direction is  $40^\circ$ . The design concept of the inner jet nozzles references the principle of the air

ejector. A high-speed jet formed by compressed air will produce a negative pressure suction effect, and then, the air inside the drill bit will be forced to form reverse circulation. The upper and lower drill bits are, respectively, designed with a kidney-shaped groove and a shaft with the same shape, which are connected by a pin shaft. Furthermore, the pin shaft is locked by snap rings, which are installed at both ends. Four flushing nozzles are designed on the drill bit. Air will flow through these flushing nozzles to the bottom of the drill bit to cool the carbide inserts. In addition, the cuttings can be carried by air into the center channel of the drill bit. Figure 2 shows that there is a crescent-shaped gap on the side of the bit when the bit swings outward. A suction channel is designed on the upper part of the bit to prevent the gathering of the cuttings since the cuttings can be sucked into the center channel directly. This is particularly important for large diameter drilling. In addition, in order to shorten the path of the cuttings into the center channel, facing the rotation direction, three involute spiral grooves are designed on the bottom surface of the lower drill bit.

**2.2. Working Principle of the Drill Bit.** When drilling begins, the rotation of the upper drill bit will drive the lower drill bit. When the lower part of the bit is in contact with the rock, there is resistance between the bit and rock. At this time, the upper drill bit will force the lower drill bit to rotate through the shaft and the groove. The unique shape of the kidney-shaped structure will lead to uneven pressure distribution between the bit and rock. In addition, the shaft is slightly smaller than the groove. Thus, the lower bit will swing outward along the kidney-shaped groove. This allows it to drill a hole slightly larger than the casing. After the lower drill bit is completely opened, the central channel and the flushing nozzles of the upper and lower drill bits are connected, and the compressed air exhausted from the DTH hammer enters the retractable bit (see Figure 3). A part of the air is sucked from the inner jet nozzles at high speed, resulting in decreased pressure around the nozzles. In this case, there will be a pressure difference between the central channel of the bit and the bottom of the borehole, and then, the cuttings and air will be sucked into the central channel. Additionally, the

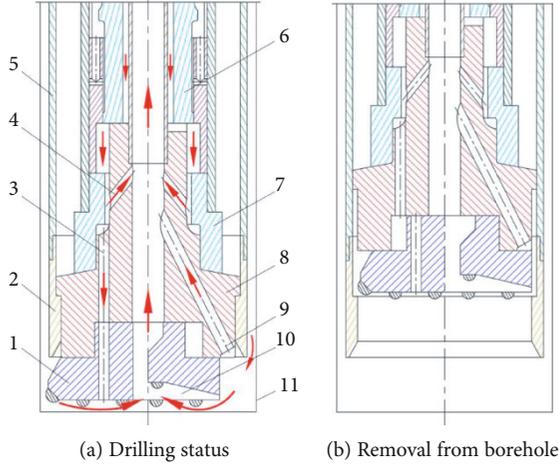


FIGURE 3: Air circulation in drilling. 1: lower drill bit; 2: casing shoe; 3: flushing nozzles; 4: inner jet nozzles; 5: casing; 6: air hammer; 7: splined sleeve; 8: upper drill bit body; 9: suction channel; 10: spiral slots; 11: borehole wall.

other part of the air flows into the flushing nozzles and sweeps the cuttings to the center channel. For the same reason, the cuttings generated near the wellbore can be directly sucked into the central channel of the drill bit through the suction channel. Under the entrainment of air flow, all the air will be mixed near the inner jet nozzles and continue to flow upward until they are carried into the cyclone on the ground. After drilling, lifting the drill bit can make the lower part of the drill bit retract into the casing so that the entire drilling system can be removed from the casing (see Figure 3(b)).

Based on the analysis of the movement of the retractable mechanism and the air circulation process inside the bit, the working principle of a retractable reverse circulation bit is proposed. A certain amount of air is injected into the drilling system through the air compressor. Due to the special gas channel structure of the drill bit, the additional air will be further sucked from the formation and the annular space between the wellbore and the drill bit. Therefore, the performance of the bit can be measured by the entrainment rate  $\eta$ , which is defined as the ratio of the mass flow rate of the air sucked into the bit from the annular space between the wellbore and the drill bit to the mass flow rate of the air supplied,

$$\eta = \frac{m_2}{m_1} \times 100\%, \quad (1)$$

where  $m_1$  and  $m_2$  are the mass flow rates of the air supplied from the compressor and the air sucked into the bit from the ambient surroundings (kg/h), respectively.

Under a given operating condition, the more air that is sucked into the drill bit, the higher the value of the entrainment ratio  $\eta$ , and the better the reverse circulation effect of the drill bit.

Regarding the important influence of the structural parameters on the reverse circulation, this paper focuses on the research and analysis of inner jet nozzles, flushing noz-

zles, and suction channels using experiments and numerical simulations. In order to study the influence of the gas channel structure parameters on bit reverse circulation performance, the influence of one parameter on the bit performance is considered, and the other parameters remain unchanged at their initial or optimal values.

### 3. Numerical Solution

**3.1. Modeling and Mesh Generation.** For simplicity, the following three assumptions were made in the numerical study: First, the borehole wall was assumed to be smooth, and the clearance between the drill bit and the borehole wall was set to 2 mm. Second, the influence of the tungsten carbide inserts on the flow field was ignored, and the space between the bottom surface of the drill bit and the borehole bottom was approximately 10 mm. Finally, the influence of the drill bit rotation on the flow field was also neglected.

In light of the practical needs for engineering projects, the opening and retracting diameters of the drill bit are approximately 150 and 132 mm, respectively. The central channel diameter of the drill bit is 24 mm. According to the basic parameters of the retractable drill bit, the geometric models of the retractable drill bit were built in a 3D domain using the Autodesk Inventor software (see Figure 4(a)). In order to obtain a good quality meshing, the models were imported to Hype-Mesh to generate grids. Considering the complex structure of the retractable drill bit, a mixture of structured and unstructured body-adaptive grids was used to generate the mesh. In the vicinity of the narrow gas channel, the mesh was refined to accurately capture the complex flow phenomena and provide reliable results. In order to ensure that the meshing controls do not influence the numerical simulation, a mesh independence study was conducted (see Table 1). The independence of the simulation from the mesh density is judged by the variation of the mass flow rate of the air sucked into the drill bit from the ambient environment, that is,  $m_2$ . The final element count of the flow domain is approximately 1.1 million. The mesh details are given in Figures 4(b) and 4(c).

**3.2. Boundary Conditions and Initial Conditions.** The choice of boundary conditions is also critical to solving the gas flow inside the retractable drill bit. The boundary of the inlet of the model was selected as a mass flow inlet, with a value of 184.3 kg/h, since the output air mass flow of the air compressor is rated. When the mass flow inlet is selected, the air is considered to be a compressible fluid, so the outlets of the model, including the central outlet of the drill bit and the annular suction outlet, should be set as free pressure outlets. Furthermore, the atmospheric pressure and temperature were given under standard conditions. It should be noted that when the reverse circulation effect of the drill bit is good, the ambient air is sucked into the drill bit through the annular clearance between the bit and the borehole. Otherwise, the air from the drill bit would escape from this boundary into the environment. The mass flow rate of the air through the bit was used to estimate the actual state. If this value is positive, it means that air flows into the model, and the reverse

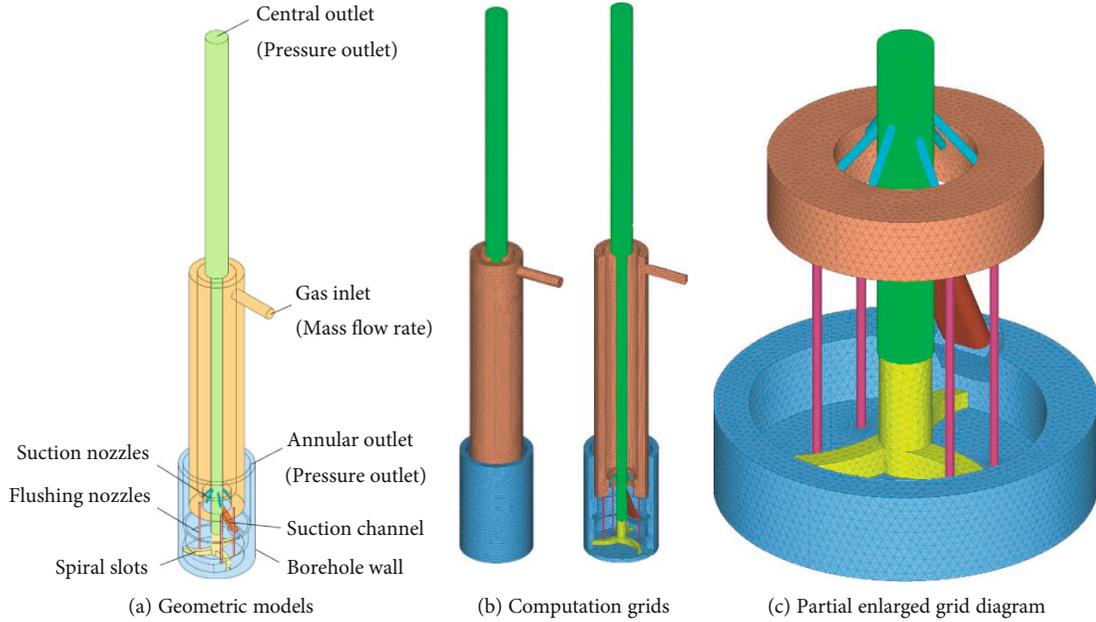


FIGURE 4: Geometric models and computation grids for the retractable drill bit with reverse circulation.

TABLE 1: Mesh independence results.

Number of mesh elements (million)	Mass flow rate at inlet, $m_1$ (kg/h)	Mass flow rate sucked into the drill bit, $m_2$ (kg/h)
0.3	184.3	56.9
0.5	184.3	50.8
0.7	184.3	47.9
0.9	184.3	46.8
1.1	184.3	44.6
1.3	184.3	44.6

circulation of the drill bit is good. If the value of the mass flow rate is negative, the opposite is true. Regarding the wall of the model, nonslip and adiabatic wall boundaries were used in all simulations, as discussed by Zhao et al. [22].

**3.3. Solution Strategy.** The three-dimensional compressible steady-state form of governing equations was solved using the finite volume technique embodied by the Ansys Fluent code, which has been covered in detail in our previous work. The coupled algorithm was selected for the pressure field. The second-order upwind scheme was used to discretize the convection diffusion terms. RNG  $k$ -epsilon, which is a transformation from the standard  $k$ -epsilon model, was utilized to simulate the turbulence flow in the study since it has certain advantages in simulating complex flows such as jets and secondary flows. The working fluid in the model is considered a compressible ideal gas, and its physical properties are available in the Fluent database. Solution convergence was evaluated by monitoring the net flux at the inlet and outlet. Furthermore, the scale residual of each governing equation should be less than  $10^{-5}$  in each simulation, as discussed elsewhere [23, 24].

#### 4. Experimental Measurements

In order to test the performance of the retractable drill bit and verify the proposed numerical model, an experimental test stand was designed (see Figure 5). A pipe open to the environment was used as the borehole. Ambient air was drawn into the drill bit through the annular clearance between the pipe and the drill bit if reverse circulation was formed. The inner jet nozzles, flushing nozzles, and suction channel will be tested under the diameters from 4 mm to 10 mm, respectively. In addition, considering the influence of the spiral groove on the reverse circulation effect, a drill bit with a straight slot and a drill bit without any slot were designed for a comparative study. The influence of the drill bit rotation on the air flow is neglected in all tests for simplicity. A compressor with the capacity of  $3 \text{ m}^3/\text{min}$  and 1.0 MPa was employed to generate air working fluid. Two LK-VFF-50 type vortex shedding flow meters were used to measure the mass flow rate of the air flowing into the testing stand from the compressor and out of the central channel, respectively. The range and precision of this type of flow meter are 0.1-100 g/s and 1.5% FS, respectively. A pressure sensor was used to measure the pressure coming from the compressor. Each test was performed three times to reduce possible experimental errors.

The retractable drill bit was produced by high-resolution laser SLA 3D printing technology with a photosensitive resin material (see Figure 6). The print precision was 0.1 mm, as discussed by Cao et al. [25].

It should be noted that the flow rate of the air mass sucked into the drill bit from the upper inlet of the casing is difficult to measure directly, whereas the outflow of air from the central channel can be conveniently monitored (see Figure 5). Thus, the flow rate of the air mass sucked into

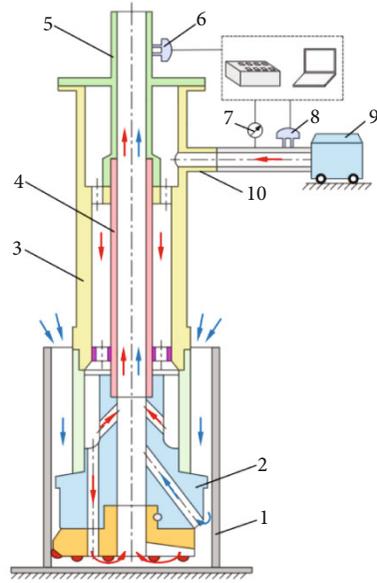


FIGURE 5: Testing stand of retractable drill bit. 1: borehole wall; 2: retractable drill bit; 3: outer drill pipe; 4: inner drill pipe; 5: outlet pipe; 6: air flow rate; 7: pressure sensor; 8: air flow rate; 9: air compressor; 10: gas inlet pipe.



FIGURE 6: 3D printed retractable drill bit.

the drill bit can be obtained by calculation. According to formula (1), the entrainment ratio  $\eta$  can be rearranged as

$$\eta = \frac{m_2}{m_1} \times 100\% = \frac{m_3 - m_1}{m_1} \times 100\%, \quad (2)$$

where  $m_3$  is the air mass flow rate outflow from the central channel (kg/h).

It is obvious that if  $\eta$  is greater than zero, reverse circulation is effectively formed since the mass flow rate of the air sucked from testing stand  $m_3$  is larger than that of the air supplied by compressor  $m_1$ . Otherwise, some of the air is exhausted into the ambient environment from the casing inlet if reverse circulation cannot be formed, which results in  $\eta$  of less than zero.

## 5. Results and Discussion

**5.1. Effect of the Flushing Nozzle Diameter.** The diameter of the inner jet nozzles was kept as 4 mm, the diameter of the

suction channel as 14.4 mm, and the shape of the bottom groove as spiral. The effect of the diameter of the flushing nozzles on the reverse circulation of the retractable drill bit has been clarified (see Figure 7(a)). As the diameter of the flushing nozzles increases, the entrainment performance of the retractable drill bit decreases. The numerical simulation and experimental results are consistent, and the results show that the entrainment ratio  $\eta$  decreases almost linearly as the diameter of the flushing nozzles increases.  $\eta$  decreases from 27.5% to -60.3% in the numerical simulation and decreases from 23.4% to -57.7% in the experiment when the diameter of the flushing nozzles increases from 4 mm to 10 mm. In order to determine the influence of the flushing nozzles on the air that flows into the drill bit, the mass flow rate of the air on the cross-section of the flushing nozzles and the inner jet nozzles of the bit is obtained (see Figure 7(b)). The mass flow rate of the air through inner jet nozzles decreases from 111.9 kg/h to 33.1 kg/h, and the mass flow rate of the air through flushing nozzles increases from 70.0 kg/h to 151.8 kg/h.

Research finds that entrainment performance relies heavily on the negative pressure formed by the high-speed air jet, which is near the inner jet nozzles. And the bottom of the borehole is considered to be connected to the atmosphere, and the pressure here is approximately equal to standard atmospheric pressure. Thus, due to the pressure difference, the air will be sucked from the bottom of the borehole to the central channel, mixed with the air from the inner jet nozzles, and then discharged to the outlet of the testing stand along the central channel.

As the diameter of the flushing nozzles increases, a large part of the air flowing into the drill bit will flow out of the flushing nozzles. The corresponding air flow into the inner jet nozzles is sharply reduced, and the magnitude velocity of the air jet is also greatly decreased (see Figure 8(a)). The

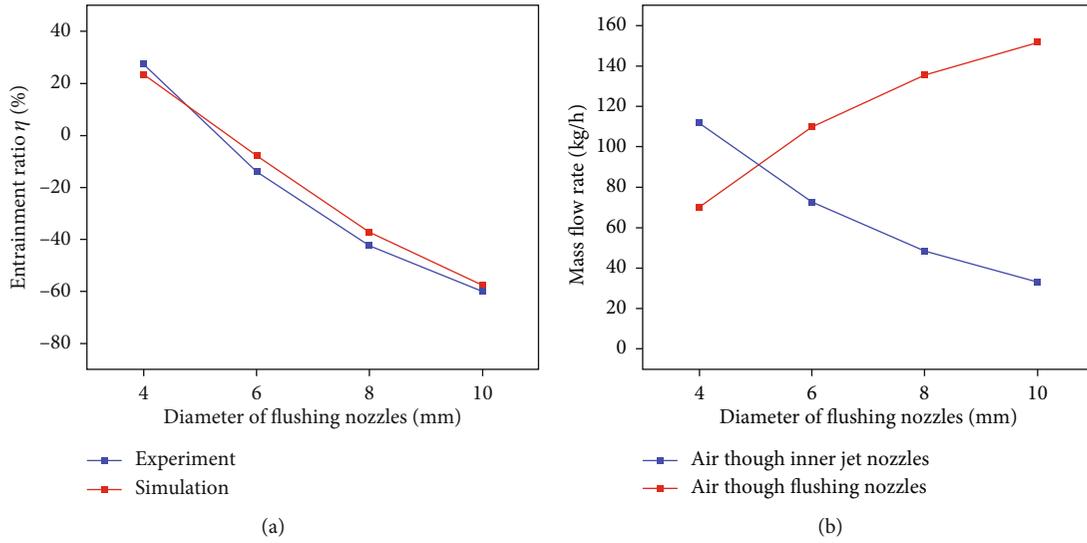


FIGURE 7: Influence of flushing nozzles on the air flow inside the drill bit: (a) air suction effect during the simulation and experiment and (b) the distribution of injected air.

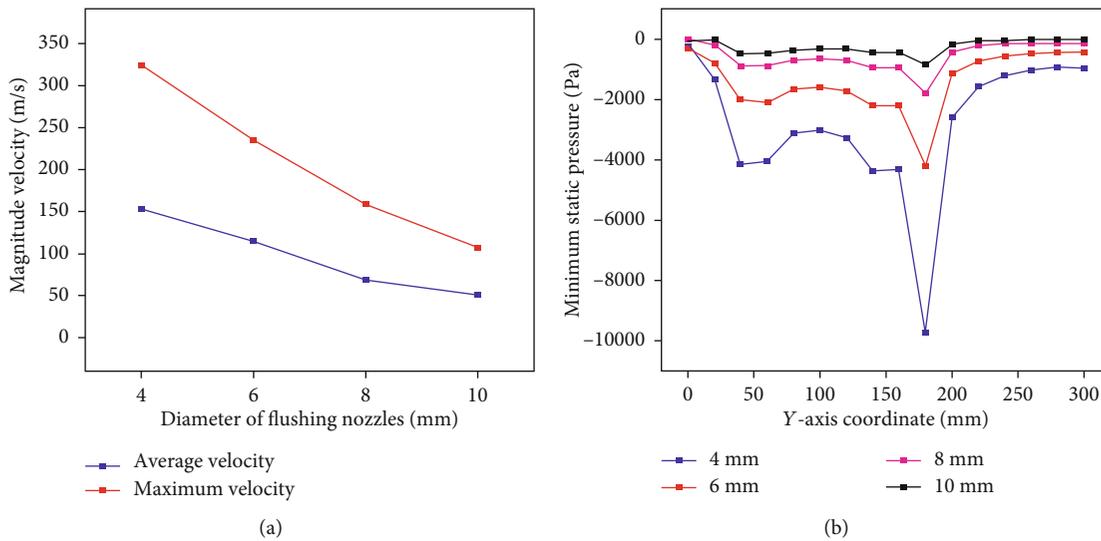


FIGURE 8: Influence of flushing nozzles on the drill bit flow field: (a) the magnitude velocity of the air jet in the inner jet nozzles and (b) the static pressure distribution along the central axis of the drill bit.

maximum magnitude velocity can reach 324.2 m/s with a diameter of 4 mm, which will directly lead to a change in the pressure distribution in the center channel of the drill bit. The cross-sections of different height positions are selected on the central channel of the drill bit, and the pressure distribution of the central channel with the change of y-axis position is obtained (see Figure 8(b)). The lowest minimum static pressure near the inner jet nozzles in the central channel is approximately -9722.8 Pa and -849.7 Pa when the diameter is 4 mm and 10 mm, respectively. Furthermore, the static pressure of the bottom of the hole is close to 0 Pa compared with the standard atmospheric pressure. Then, there will be a pressure difference between the bottom of the hole and the central channel of the bit, and the negative pressure suction will pump the air into the central channel

and form reverse circulation. The lower the static pressure is, the greater the reverse circulation effect. It is worth noting that the height of the suction channel is approximately 100 mm, and the pressure rises slightly here due to air mixing. In the same case, when the pumped air is mixed with the air injected near the inner jet nozzles, the pressure increases rapidly, and the static pressure tends to be stable after the air flow is completely mixed.

Theoretically, the smaller the diameter of the flushing nozzles is, the greater the entrainment performance the drill bit will obtain. However, in the actual drilling process, flushing nozzles must exist because of the great contribution of carrying cuttings.

Above all, the diameter of the flushing nozzles is selected to be 4 mm for the best.

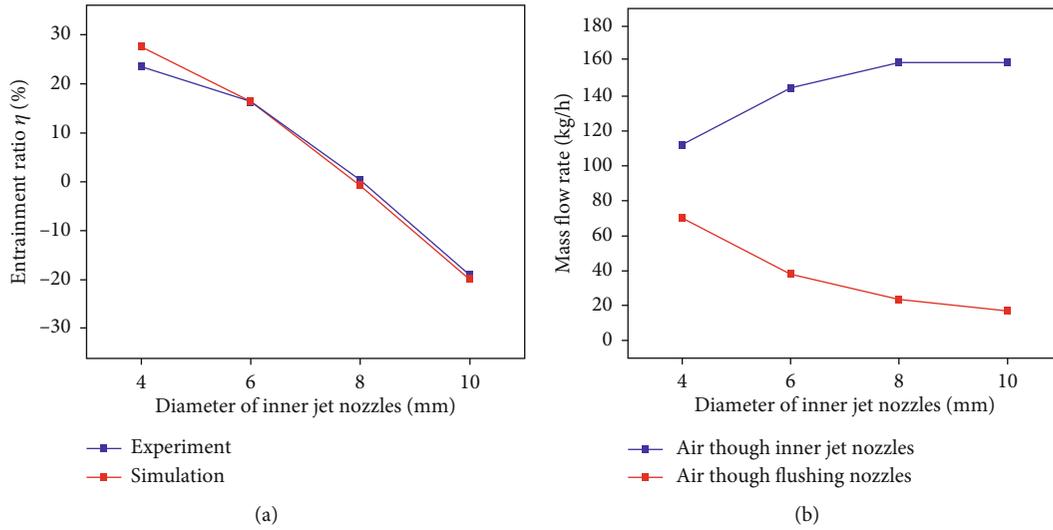


FIGURE 9: Influence of inner jet nozzles on the air flow inside the drill bit: (a) air suction effect during the simulation and experiment and (b) the distribution of injected air.

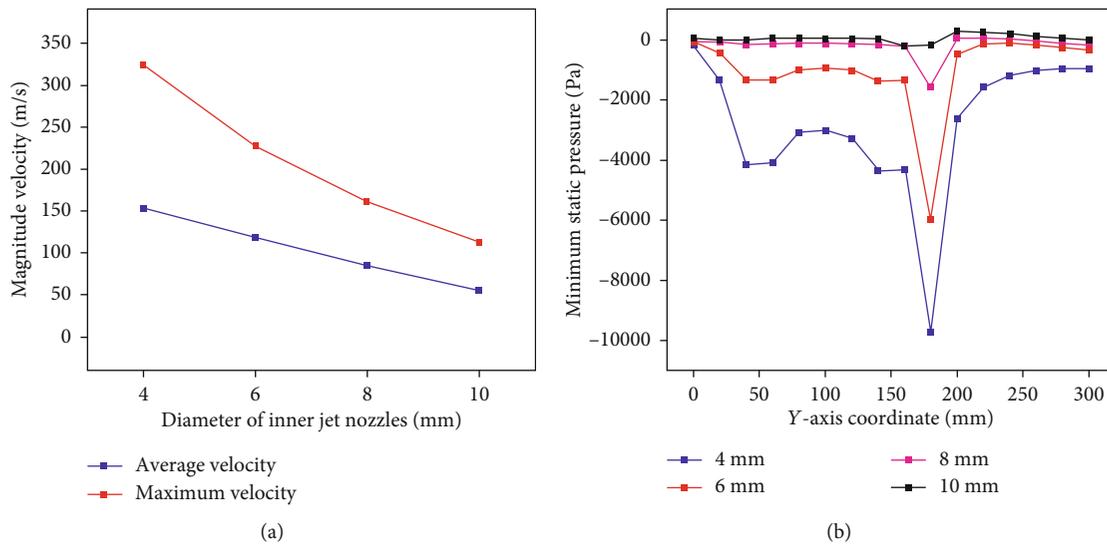


FIGURE 10: Influence of inner jet nozzles on the drill bit flow field: (a) the magnitude velocity of the air jet in the inner jet nozzles and (b) the static pressure distribution along the central axis of the drill bit.

**5.2. Effect of the Inner Jet Nozzle Diameter.** The diameter of the flushing nozzles was kept as 4 mm, the diameter of the suction channel as 14.4 mm, and the shape of the bottom groove as spiral. There is a significant effect of the diameter of the inner jet nozzles on the reverse circulation performance (see Figure 9(a)). The entrainment ratio  $\eta$  decreases as the inner jet nozzle diameter increases. There is good agreement between the numerical simulation and experiment. As with the flushing nozzles, there is an important influence of the inner jet nozzles on the distribution of the air flow into the drill bit (see Figure 9(b)). The mass flow rate of the air through inner jet nozzles increases from 111.9 kg/h to 159.0 kg/h and decreases from 67.0 kg/h to 16.7 kg/h for flushing nozzles when the diameter of the inner jet nozzles increases from 4 mm to 10 mm.

However, the entrainment performance did not improve when the air flow rate through the inner jet nozzles increased. The principal reason for this case is that the area of the nozzles changes greatly. Meanwhile, the air flow rate does not increase significantly. Therefore, the magnitude velocity of the air jet through the inner jet nozzles significantly decreases as the diameter of the inner jet nozzles increases from 4 mm to 10 mm. As shown in Figure 10(a), the maximum magnitude velocity decreases from 324.2 m/s to 113.2 m/s, and the average magnitude velocity decreases from 152.8 m/s to 55.4 m/s. The lower the magnitude velocity is, the weaker the air jet strength is, which will weaken the effect of reverse circulation. Figure 10(b) shows the minimum static pressure along the central axis of the drill bit. The static pressure is close to 0 Pa when the diameter is 10 mm and is negative

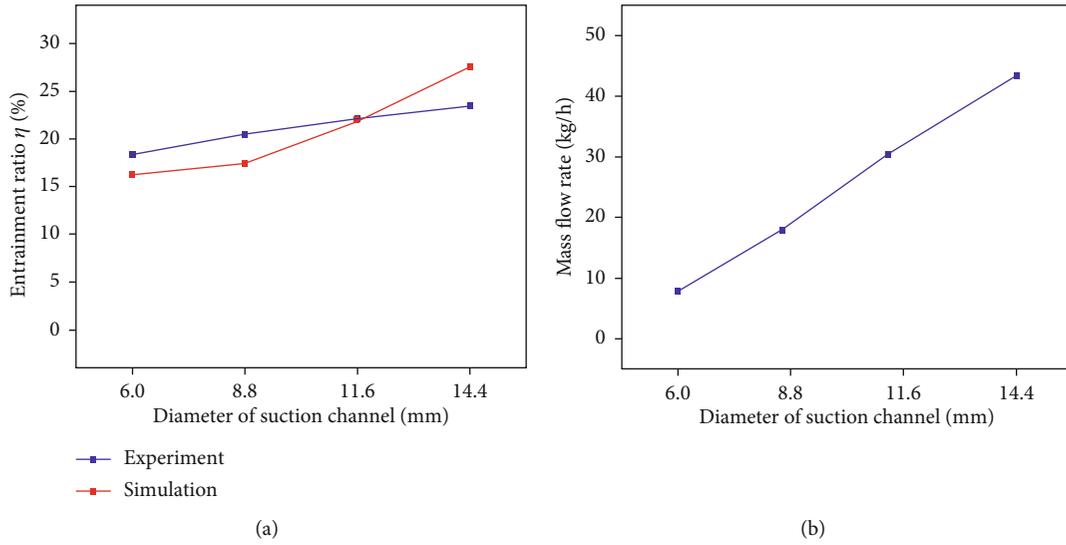


FIGURE 11: Influence of suction channel on air flow inside the drill bit: (a) air suction effect during the simulation and experiment and (b) mass flow of air through the suction channel.

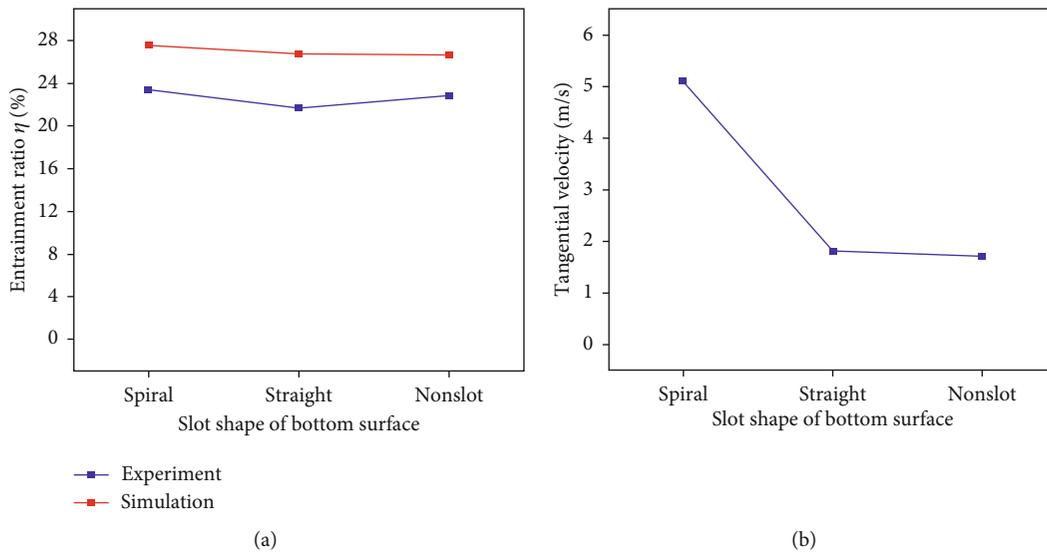


FIGURE 12: Influence of the shape of the bottom groove on the air flow inside the drill bit: (a) air suction effect during the simulation and experiment and (b) tangential velocity at the entrance of the central channel.

when the diameter is smaller than 8 mm and the minimum value is 4 mm, which indicates that the greater the diameter of the inner jet nozzles is, the worse the entrainment performance.

Based on the above analysis, the proper reduction of the diameter of the inner jet nozzles is conducive to improving the reverse circulation effect. Therefore, in this study, the best diameter of the inner jet nozzle is 4 mm.

**5.3. Effect of the Suction Channel Diameter.** For the conventional reverse circulation drill bit, the air carrying cuttings is sucked by the center channel at the bottom of the bit. However, for the retractable drill bit, a suction channel is designed at the bottom of the drill bit. The existence of the suction channel increases the space for air to enter the drill bit. As

a result, the external air is more easily sucked into the center channel of the bit from the annular space between the wellbore and the drill bit. Thus, the reverse circulation effect is effectively improved. The diameter of the inner jet nozzles was kept as 4 mm, the diameter of the flushing nozzles as 4 mm, and the shape of the bottom groove as spiral. Both numerical simulations and experiments show that the entrainment performance improves as the diameter of the suction channel increases (see Figure 11(a)). Furthermore, Figure 11(b) shows that the mass flow rate of the air through the suction channel increases from 7.8 kg/h to 42.9 kg/h as the diameter increases from 6.0 mm to 14.4 mm.

The size of the suction channel is limited by the opening displacement of the drill bit, so choosing as large of a suction channel as possible can effectively improve the reverse

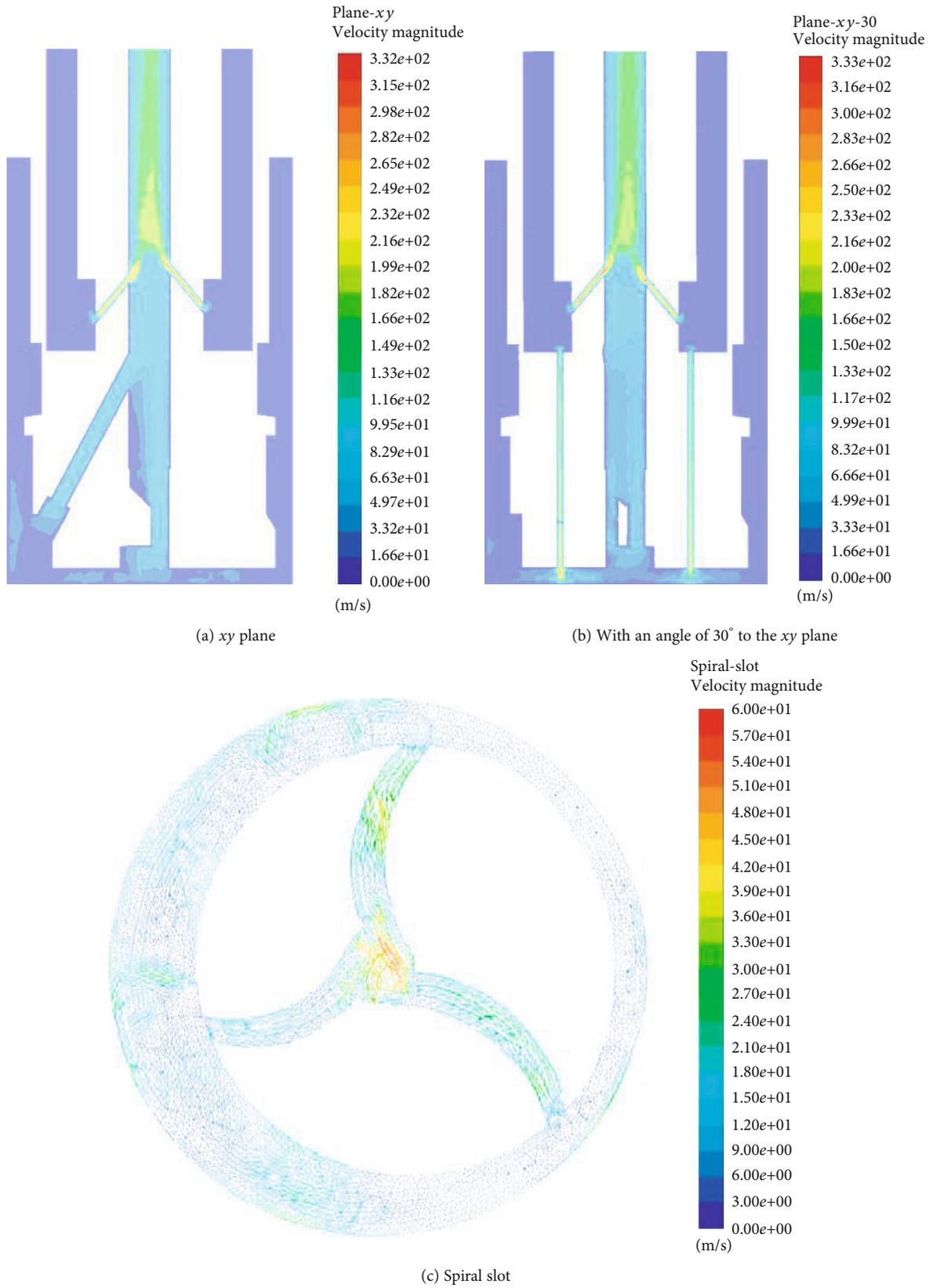


FIGURE 13: Velocity magnitude in the flow field of the optimal drill bit.

circulation effect. In this study, the diameter of the suction channel was set as 14.4 mm.

**5.4. Effect of the Shape of the Bottom Groove.** In order to explore the performance of the reverse circulation for different shapes of the bottom groove, three types of the lower drill bits were tested, respectively. The diameter of the inner jet nozzles was kept as 4 mm, the diameter of the flushing nozzles as 4 mm, and the diameter of the suction channel as 14.4 mm. The experimental results show that the maximum entrainment ratio  $\eta$  is 23.43% for the spiral slot, and the minimum entrainment ratio  $\eta$  is 21.59% for the straight slot (see Figure 12(a)). Different from the experimental results, the entrainment ratio  $\eta$  of nonslot is the minimum in the numerical simulation. The complex flow field at the bottom of the hole leads to some deviation between the two results. However, there is little difference between straight slot and nonslot, whether in the experimental or in the numerical simulation. Thus, they are considered to have a trifling impact on the reverse circulation effect.

The numerical simulation results show that the tangential velocity of the drill bit with a spiral slot is significantly higher than those of the other two types of drill bits at the entrance of the central channel (see Figure 12(b)). The tangential velocity of the drill bit without a slot is basically the same as that of the drill bit with a straight slot. However, the maximum tangential velocity can reach 5.1 m/s for the spiral slot, which is approximately 200% higher than that of the nonslot drill bits. That is, the spiral slot can make the air carrying cuttings enter into the central channel in the form of a spiral flow, which can reduce the energy consumption of air-solid collision and weaken the resistance of the air entering into the central channel. Thus, the drill bit with a spiral slot is conducive to improving the reverse circulation effect.

Experiments and simulation analysis indicate that the best combination for the drill bit is inner jet nozzles with a diameter of 4 mm, flushing nozzles with a diameter of 4 mm, and a suction channel with a diameter of 14.4 mm. The spiral slot designed on the bottom surface of the drill bit can significantly help the air flow into the central channel. Figures 13(a) and 13(b) illustrate the velocity magnitude contours of the optimal drill bit. With the compressed air flowing into the center channel through inner jet nozzles, an air jet with high velocity is mixed with the suction air and then flows upward out of the test stand. The setting of the suction channel makes it easier for the air to be sucked into the center channel. And the air jets flowing out of the flushing nozzles at the borehole bottom can stir up the air and help push them into the drill bit. Furthermore, the air at the bottom of the hole flows into the central channel in the form of swirling flow along the spiral groove (see Figure 13(c)). The air in the outer regions flows into the central area, which indicates the formation of reverse circulation at the borehole bottom.

## 6. Conclusions

- (1) A reverse circulation DTH hammer drill bit of CwD is designed and applied to drilling under complicated

formation. It is a special retractable drill bit with exclusive reverse circulation gas channels. These gas channels enable the bit to form a strong air reverse circulation and ensure a clean, wellbore environment

- (2) Numerical simulation and experimental methods were employed to investigate the influence of the structural parameters of the drill bit, including the diameters of the inner jet nozzles, flushing nozzles, and suction channel and the slot shape on the bottom surface of the drill bit, on its reverse circulation performance. Moreover, the results are highly consistent between the two approaches. And the research will be helpful for designing and application of the reverse circulation DTH hammer drill bit of CwD
- (3) It is observed that the flushing nozzles and inner jet nozzles have important influences on entrainment performance. Changing their diameters affects the flow distribution of the input air. The entrainment rate  $\eta$  decreases as the diameter of the flushing nozzles increases and decreases as the diameter of inner jet nozzles increases. An increase in the diameter of the suction channel can improve the reverse circulation effect of the drill bit. The shape of the bottom groove has no significant effect on the performance of reverse circulation, but the spiral slot drill bit is more conducive to the air being sucked into the central channel in the form of a spiral flow; therefore, it can improve the effect of entrainment performance
- (4) Analysis shows that the best combination for the drill bit is a flushing nozzle diameter of 4 mm, an inner jet nozzle diameter of 4 mm, and a suction channel diameter of 14.4 mm. In addition, the spiral slot designed on the bottom surface of the drill bit can help to improve the reverse circulation effect. Furthermore, the entrainment rate  $\eta$  can reach 23.4% with the optimum structured drill bit

## Data Availability

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (qibo18@mails.jlu.edu.cn).

## Conflicts of Interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication.

## Acknowledgments

This work was supported by the National Key Research and Development Project of China (project no. 2018YFC1505303) and Natural Science Foundation of Jilin Province (YDZJ202101ZYTS143).

## References

- [1] S. Medhi, D. K. Gupta, and J. S. Sangwai, "Impact of zinc oxide nanoparticles on the rheological and fluid-loss properties, and the hydraulic performance of non-damaging drilling fluid," *Journal of Natural Gas Science and Engineering*, vol. 88, p. 103843, 2021.
- [2] S. H. Hajiabadi, H. Aghaei, M. Ghabdian, M. Kalateh-Aghamohammadi, E. Esmailnezhad, and H. J. Choi, "On the attributes of invert-emulsion drilling fluids modified with graphene oxide/inorganic complexes," *Journal of Industrial and Engineering Chemistry*, vol. 93, pp. 290–301, 2021.
- [3] D. Kuanhai, P. Xie, Y. Yue, Z. Dezhi, L. Qiong, and L. Yuanhua, "Study on the effect of interface failure between casing and cement sheath on casing stress under non-uniform in-situ stress," *Applied Mathematical Modelling*, vol. 91, pp. 632–652, 2021.
- [4] R. Ashena, A. Elmgerbi, V. Rasouli, A. Ghalambor, M. Rabiei, and A. Bahrami, "Severe wellbore instability in a complex lithology formation necessitating casing while drilling and continuous circulation system," *Journal of Petroleum Exploration and Production Technology*, vol. 10, no. 4, pp. 1511–1532, 2020.
- [5] X. Zhang, Y. Wu, E. Zhai, and P. Ye, "Coupling analysis of the heat-water dynamics and frozen depth in a seasonally frozen zone," *Journal of Hydrology*, vol. 593, p. 125603, 2021.
- [6] X. Zhang, Y. Lu, J. Yao, Y. Wu, Q. C. Tran, and Q. V. Vu, "Insight into conditioning landfill sludge with ferric chloride and a Fenton reagent: effects on the consolidation properties and advanced dewatering," *Chemosphere*, vol. 252, p. 126528, 2020.
- [7] X. Zhang, E. Zhai, Y. Wu, D. A. Sun, and Y. Lu, "Theoretical and numerical analyses on hydro-thermal-salt-mechanical interaction of unsaturated salinized soil subjected to typical unidirectional freezing process," *International Journal of Geomechanics*, vol. 21, no. 7, article 04021104, 2021.
- [8] A. Mohammed and C. J. Okeke, "Current trends and future development in casing drilling," *International Journal of Science and Technology*, vol. 2, no. 8, pp. 576–582, 2012.
- [9] J. Peng, D. Ge, X. Zhang, M. Wang, and D. Wu, "Fluidic DTH hammer with backward-impact-damping design for hard rock drilling," *Journal of Petroleum Science and Engineering*, vol. 171, pp. 1077–1083, 2018.
- [10] T. Warren, B. Houtchens, and G. Madell, "Directional drilling with casing," in *SPE/IADC Drilling Conference*, vol. 79914, pp. 1–10, Amsterdam, The Netherlands, 19–21 February 2003.
- [11] T. Saksala, M. Fourmeau, P. A. Kane, and M. Hokka, "3D finite elements modelling of percussive rock drilling: estimation of rate of penetration based on multiple impact simulations with a commercial drill bit," *Computers and Geotechnics*, vol. 99, pp. 55–63, 2018.
- [12] L. E. Chiang and D. A. Elōas, "Modeling impact in down-the-hole rock drilling," *International Journal of Rock Mechanics and Mining Sciences*, vol. 37, no. 4, pp. 599–613, 2000.
- [13] P. L. Cao, Y. W. Chen, M. M. Liu, and B. Y. Chen, "Optimal design of novel drill bit to control dust in down-the-hole hammer reverse circulation drilling," *Arabian Journal for Science and Engineering*, vol. 43, no. 3, pp. 1313–1324, 2016.
- [14] Y. Luo, J. Peng, L. Li et al., "Development of a specially designed drill bit for down-the-hole air hammer to reduce dust production in the drilling process," *Journal of Cleaner Production*, vol. 112, pp. 1040–1048, 2016.
- [15] S. Q. Hao and H. W. Huang, "Air reverse circulation bit internal fluid simulation based on CFD," in *International Conference on Information Technology and Computer Science*, Kiev, Ukraine, 2009.
- [16] P. L. Cao, M. M. Liu, Y. W. Chen, and J. S. Wang, "Analytical and experimental study of a reverse circulation drill bit with an annular slit," *Advances in Mechanical Engineering*, vol. 8, no. 9, 10 pages, 2017.
- [17] V. V. Timonin, S. E. Alekseev, V. N. Karpov, and E. M. Chernienkov, "Influence of DTH hammer impact energy on drilling-with-casing system performance," *Journal of Mining Science*, vol. 54, no. 1, pp. 53–60, 2018.
- [18] D. Ravi, S. Yohannes, B. Koteswararao, K. Satish, and K. S. Kishorebabu, "Structural analysis of down the hole button bit with different materials," *Materials Today: Proceedings*, vol. 5, pp. 4711–4719, 2018.
- [19] Y. Z. Wu and L. P. Wu, "Novel oscillating orientation device of DTH hammer for hard rock stratum non-dig drilling," *ICPTT 2011: Sustainable Solutions For Water, Sewer, Gas, And Oil Pipelines*, 2011.
- [20] X. X. Zhang, Y. J. Luo, X. Gan, and K. Yin, "Design and numerical analysis of a large-diameter air reverse circulation drill bit for reverse circulation down-the-hole air hammer drilling," *Energy Science & Engineering*, vol. 7, no. 3, pp. 921–929, 2019.
- [21] Y. Zhou, D. Zhao, B. Li, H. Wang, Q. Tang, and Z. Zhang, "Fatigue damage mechanism and deformation behaviour of granite under ultrahigh-frequency cyclic loading conditions," *Rock Mechanics and Rock Engineering*, 2021.
- [22] Z. Q. Zhao, L. J. Li, K. Bo, X. S. He, and J. F. Chai, "Numerical investigation based on orthogonal design of structural parameters on large-diameter DTH hammer bit," *Advanced Materials Research*, vol. 774, pp. 1442–1445, 2013.
- [23] K. Bo, M. S. Wang, and Z. Q. Zhao, "Numerical simulation on bottom hole flow fields of reverse circulation bit," *Applied Mechanics and Materials*, vol. 256, pp. 2826–2830, 2012.
- [24] H. Z. Shi, H. Y. Song, H. Q. Zhao, and Z. L. Chen, "Numerical study of a flow field near the bit for a coiled-tubing partial underbalanced drilling method," *Journal of Energy Resources Technology*, vol. 141, pp. 1–11, 2019.
- [25] P. L. Cao, Q. Zhao, Z. Chen, H. Y. Cao, and B. Y. Chen, "Orthogonal experimental research on the structural parameters of a novel drill bit used for ice core drilling with air reverse circulation," *Journal of Glaciology*, vol. 65, no. 254, pp. 1011–1022, 2019.