

## Article

# Flow Field Simulation of a Hydrogeological Exploration Drill Bit for Switching between Coring Drilling and Non-Coring Drilling

Yuanling Shi <sup>1,2,\*</sup>  and Conghui Li <sup>1</sup> 

<sup>1</sup> School of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, China; lichonghuitxwd@126.com

<sup>2</sup> Academician Workstation in Anhui Province, Anhui University of Science and Technology, Huainan 232001, China

\* Correspondence: ylshi@aust.edu.cn

**Abstract:** Drilling is one of the most commonly used techniques in hydrogeological exploration and is employed to obtain rock samples and create boreholes. During conventional drilling, it is necessary to raise all the drilling tools in the borehole when switching between coring drilling and non-coring drilling, which causes large auxiliary operation time consumption and poor drilling efficiency. Based on the structure of wireline coring tools, a large diameter modular drill bit was designed to switch between coring drilling and non-coring drilling without lifting the whole set of drilling tools. In the COMSOL simulation environment, a simulation model of the modular bit was constructed. Drilling fluid velocity and pressure characteristics flowing through the modular bit were studied. According to the analysis results, with the same input flow rate, similar velocities and lower pressure loss can be obtained in non-coring drilling as with the coring bit, and thus drilling cuttings can be removed effectively even if there are more cuttings produced in non-coring drilling than in coring drilling for a borehole drilled at the same diameter. When the outside diameter of the modular bit is 216 mm, the recommended clearance value is 9 mm or 10 mm in order to obtain lower pressure loss and larger diameter core. To generate low pressure loss and ensure bit strength, a layout with four nozzles on the internal non-coring bit is recommended. The modular bit enables fast switching between coring drilling and non-coring drilling without raising the drilling tools. The simulation model can be used for drilling parameter selection and drill bit optimization.



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**Keywords:** large diameter modular drill bit; drill bit design; CFD simulation; flow field characteristics

## 1. Introduction

Geological exploration is an important means of identifying geological conditions, analyzing geological problems, and studying geological characteristics and laws of evolution, which play a key role in fields like engineering geology, hydrogeology, mineral investigation, and oil and gas exploration. Taking hydrogeological survey as an example, the causes, distribution, and movement patterns of groundwater and surface water could be obtained using this method, thereby providing a foundation for water evaluation and utilization [1]. In previous geological exploration, groundwater has often been overlooked, resulting in significant accidents. In hydrogeological surveys, activities such as collecting geological and hydrogeological data, conducting geophysical exploration and hydrogeological drilling, analyzing hydrogeological data, and simulating and predicting groundwater behavior, should be involved [2,3]. Among these, drilling is one of the most commonly used techniques in hydrogeological surveys and is employed to obtain rock samples and create boreholes, thus providing crucial information about stratigraphic texture, formation properties, and groundwater levels. From the perspective of whether or not to obtain cores, drilling can be divided into coring drilling and non-coring drilling. By coring drilling, cores are obtained at target formations [4,5], which serve as an important source of strata data

in hydrogeological surveys. By testing and analyzing the cores, composition, structure, thickness, and properties of formation can be studied, and groundwater properties can be evaluated. With non-coring drilling, boreholes are drilled quickly and safely [6] to provide channels for groundwater collection and hydrological observation. Therefore, in hydrogeological surveys, both coring drilling and non-coring drilling are needed. During the drilling process, depending on the specific drilling purpose, it is sometimes needs to switch between the above two drilling methods.

Currently, when switching between coring drilling and non-coring drilling, it is usually necessary to lift all the drilling tools out of the boreholes and replace the current drill bits with the appropriate ones. As the depth of boreholes increases, it will take a longer time to raise and drop the whole set of drilling tools in the boreholes, which reduces drilling efficiency, increases labor intensity, and raises drilling costs [7–9]. Thus, there is an urgent issue to be solved for switching between coring drilling and non-coring drilling without lifting the whole set of drilling tools. Previous studies on replacing drill bits without lifting all the drilling tools out of the borehole mainly focused on changing the diameter of the drill bit through special structures, which could not achieve the conversion between coring drilling and non-coring processes. In the literature [10], a drilling device for changing between coring drilling and non-coring drilling without lifting the drill pipes was designed. Based on the structure of wireline coring systems, it is only necessary to lift the inner tube assembly and replace the required drill bits when switching between coring drilling and non-coring drilling, which can improve drilling efficiency greatly. Based on that drill structure, a new modular bit for switching between coring drilling and non-coring drilling is proposed.

During drilling, the drill bit is driven by rigs or downhole motors to rotate and break rocks in the borehole. While drilling, fluid is pumped into the boreholes to balance formation pressure, cool and lubricate the drilling tools, and remove rock cuttings in a continuous cycle. Drill bit structure will affect the cooling effect of drilling fluid. This is because varying flow field characteristics will be generated when drilling fluid flows in flow channels with different structures. Computational fluid dynamics (CFD for short) is a popular method for drill bit flow field analysis at present and is widely used in drill bit structure design and optimization [11–13]. As repeated fragmentation of large limestone cuttings would reduce drilling efficiency, Zhu et al. analyzed a geophysical drill bit using the CFD method and optimized its hydraulic structure based on its flow field results [14]. Cao et al. analyzed the characteristics of the two-phase flow field of a diamond bit for KM closed coring drilling tools using the numerical simulation method and put forward design suggestions for the two-phase flow channel of a diamond bit [15]. Wang et al. designed a set of undersea diamond coring bits, which can effectively protect the rock core samples, and analyzed the flow characteristics of drilling fluid flowing in boreholes using Fluent software (<https://springer.longhoo.net/article/10.1186/s44147-022-00135-y>, 22 August 2022) [16]. In the literature [17], flow field distribution of a PDC bit was studied using the finite element simulation method, and a PDC bit design method was proposed for drilling tight oil reservoirs. Hajipour studied turbulent two- phase flow in horizontal wellbores and investigated various parameters on cuttings transport using CFD analysis [18]. Zhang designed a set of air reverse circulation drill bits and improved their suction abilities by using the theory of numerical simulation [19]. In the literature [20], a novel reverse circulation bit was designed, inside which swirling flow could be generated, and the swirling flow phenomenon was simulated through ANSYS Fluent.

In this paper, a modular drill bit for coring drilling and non-coring drilling was designed in the second part, which can be applied to large diameter hydrogeological well drilling. In Section 3, a simulation model based on the CFD method was established using the COMSOL software (trial version), which is utilized to study flow characteristics coupled with the bit and drilling fluids. In Section 4, the velocity and pressure of drilling fluid flowing through the modular bit are analyzed, considering the factors of inlet flow rate,

clearance between the external bit and internal bit for coring drilling, and layout of the nozzles at the bottom of the internal bit for non-coring drilling.

## 2. Structure Design of the Modular Drill Bit

A modular bit to enable switching between coring drilling and non-coring drilling without lifting the whole set of drilling tools was designed according to the structure of wireline coring systems, as in Figure 1. This drill bit includes an external bit (1), two kinds of internal bits (2) and (5), an isolating casing (3), and a torque ring (4). The external bit (1) can be connected to an outer tube of a conventional wireline coring system using threads, whereby speed and torque for cutting rocks can be obtained from the drill pipes. The isolating casing (3) and the torsion ring (4) are installed inside the external bit (1). On the isolating casing, several radial holes (b) are opened, where drilling fluid flows from the clearance between the external bit and the internal bit to nozzles on the external bit. There are two group of splines on the outside and inside of the torque ring (c, d), which can mesh with the splines inside the external drill bit (e) and splines outside the internal bit (a), respectively. Through the above splines, the rotation speed and torque of the external bit can be transmitted to the internal bit, ensuring synchronous rotation between the two bits and enabling effective rock cutting. The two kinds of internal bits are a coring bit (2) and a non-coring bit (5), which can be connected to the inner tube assembly of a wireline coring system. To switch from coring drilling to non-coring drilling just requires pulling out the inner tube assembly and changing the coring bit to the non-coring one without lifting the whole set of drilling tools from the borehole. Conversely, the same steps can be taken to change the non-coring bit to the coring bit. In this paper, several modular bits designed for drilling boreholes with a diameter of 216 mm are described. The external drill bit with a hollow structure has an outside diameter of 216 mm and a minimum inside diameter of 105 mm at the bottom. Six nozzles (f) are arranged on the external drill bit, through which drilling fluid can flow to the borehole bottom. The internal coring drill bit is a hollow impregnated diamond bit which can obtain rock cores with a diameter of 58 mm. Meanwhile, the internal non-coring bit is also equipped with several nozzles (h) on its bottom, used for drilling fluid circulation and hydraulic rock fragmentation.

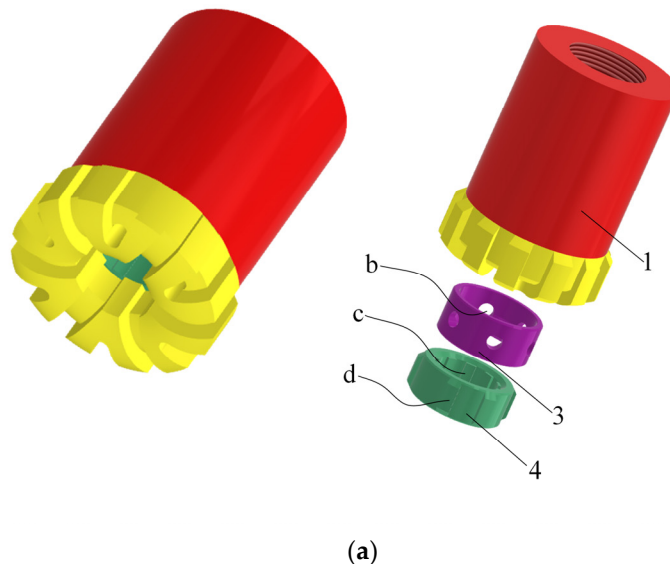


Figure 1. Cont.

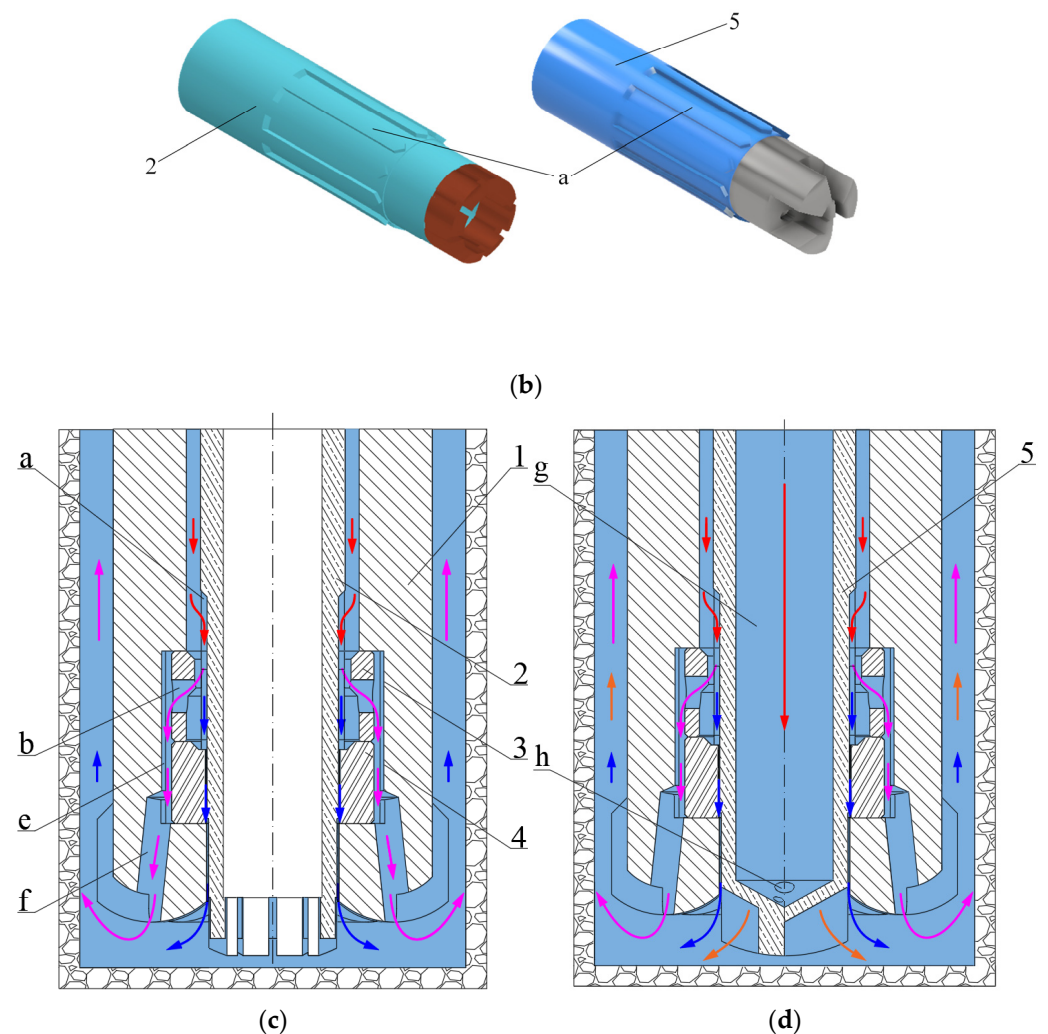


**Figure 1.** Construction of the large diameter modular bit: (a) 3D model of the external bit; (b) 3D model of the coring and non-coring internal bits; (c) internal structure of the coring drill bit; (d) internal structure of the non-coring drill bit. 1—external bit; 2—internal coring bit; 3—isolating casing; 4—torque ring; 5—internal non-coring bit; a—spline on the internal bit; b—radial holes on the isolating casing; c—spline on the inside of the torque ring; d—spline on the outside of the torque ring; e—spline on the external bit; f—bottom nozzles of the external bit; g—center channel of the internal non-coring bit; h—bottom nozzles of the internal non-coring bit.

As Figure 1c,d show, the drilling fluid circulating process is different for the coring bit and non-coring bit. When coring drilling, drilling fluid flows into the clearance between the external bit and internal bit. Then, most of it reaches the bottom of boreholes through radial holes on the isolating casing and nozzles on the external bit, while the remainder of the drilling fluid flows to the borehole bottom through the clearance between the isolating casing and the internal coring bit. Finally, the above two streams of the fluid meet at the borehole bottom and, subsequently, return along the annular clearance between the external bit and borehole wall. During non-coring drilling, a small amount of drilling fluid flows to the borehole bottom via the clearance between the external bit and internal bit, while most of the drilling fluid flows to borehole bottom via the central channel of the internal non-coring bit and is jetted out from the its bottom nozzles. Then, the drilling fluid converges at the borehole bottom and flows upward.

### 3. CFD Model of the Large Diameter Modular Drill Bit

During drilling, drilling fluids are pumped from the ground into boreholes and continuously circulated between the ground and boreholes to remove rock cuttings, lubricate and cool drill bits, and maintain the stability of boreholes. Usually, drilling fluid pressure in the borehole is balanced with the formation pressure to prevent formation fluids from entering the borehole and causing accidents, while also preventing drilling fluids from leaking into the formation and polluting the formation. As a tool for breaking rocks, a drill bit generally cuts rocks using weight and rotation, and multiphase drilling fluids are circulated inside and outside of it. In order to ensure minimal pressure loss after drilling fluids flowing through the drill bit and sufficient flow velocities to carry rock cuttings, the water gaps on the drill bit, the annular clearance between the drill bit and borehole wall, and the clearance between the drill bit and borehole bottom, all should be designed carefully. In this section, a flow field simulation model of the modular drill bit is established using the CFD method. This model can be used for analyzing the rationale of the drill bit structure and optimizing the design scheme.

#### 3.1. Fluid Domain and Meshing

Due to unpredictable formation conditions, time-varying stress state of drilling tools, irregular borehole bottom, and wear of drill bit, simplification was introduced when the drill bit simulation model was built. Firstly, since the linear velocity of a drill bit is much lower than the flow velocities of the drilling fluid, drill bit rotation was not considered when constructing the model to study flow field characteristics [21,22]. Secondly, in order to decrease the calculation time and enhance the convergence rate, the fillets, chamfers, and other structures that did not affect the calculation results, were ignored. Meanwhile, for the convenience of establishing the fluid domain, the isolation casing, torque ring, the rock at the drill bit bottom, and the external bit, were combined into one part.

A physical model of a modular drill bit was built using CAD software (Inventor education version) and imported into COMSOL software, and the fluid domain of the modular bit was created using the geometric component construction module by Boolean operation, as shown in Figure 2. The fluid domain of the coring bit includes the clearance between external bit and internal bit, the radial holes on the isolating casing, the chamber between the external bit and the torque ring, the nozzles of the external bit, the water gaps on the external bit, the chamber between the isolating casing and internal bit, the passageways between the torque ring and the internal bit, the water gap on the internal bit, and the annulus clearance between the external bit and borehole wall. The fluid domain of the non-coring bit includes the clearance between the external bit and the internal bit, the radial holes of the isolating casing, the chamber between the external bit and the torque ring, the nozzles on the external bit, the water gaps on the external bit, the chamber between the isolating casing and the internal bit, the passageways between the torque ring and the internal bit, the water gaps on the internal bit, the central channel of the internal non-coring bit, the nozzles on the internal non-coring bit, and the annulus between the external bit and borehole wall.

Because the waterways on this modular drill bit are very complex and narrow, dividing high quality meshes is quite difficult and demanding, and reasonable mesh density is an important prerequisite for improving the accuracy of flow field calculation [23–25]. For the drill bit simulation model, unstructured tetrahedral meshes were introduced to speed up calculation and increase precision of the results. To ensure the accuracy of the simulation, this study includes an analysis of mesh independence. For example, for the coring drill bit, when the inlet flow rate was set to 300 L/min and the clearance between the external bit and the internal bit was 9 mm, the flow field model was simulated using three different mesh divisions, as shown in Table 1. Finer meshes resulted in longer computation times but provided more accurate results. Therefore, within the limits of hardware capabilities, a refined mesh was used for the calculations to ensure the accuracy of the model.

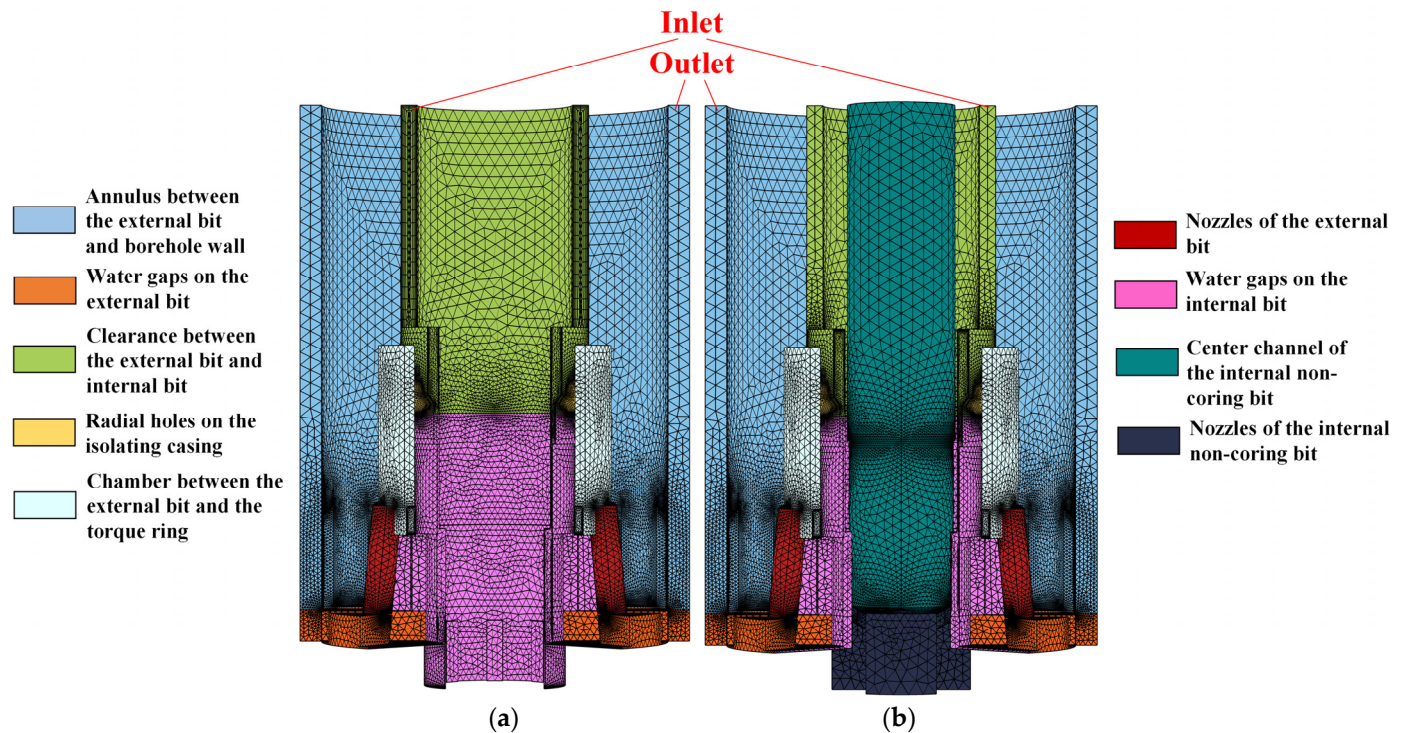


**Figure 2.** Fluid domain model meshing of the modular drill bit: (a) coring bit; (b) non-coring bit.

**Table 1.** Mesh independence study.

| Mesh Tape   | Number of Elements | Degrees of Freedom for Solving | Computation Time | Outlet Return Velocity (m/s) | Inlet Pressure (Pa) |
|-------------|--------------------|--------------------------------|------------------|------------------------------|---------------------|
| Coarse mesh | 1,211,801          | 2,477,407                      | 5 min, 10 s      | 0.72                         | 19,868              |
| Medium mesh | 243,296            | 521,245                        | 11 min, 24 s     | 0.70                         | 19,657              |
| Fine mesh   | 133,327            | 294,889                        | 1 h, 19 min, 8 s | 0.71                         | 18,760              |

### 3.2. Governing Equations and Boundary Conditions for the CFD Simulation

Model parameters and boundary conditions play critical roles in CFD model calculation and analysis, which directly affect the accuracy of the final results [26,27]. There are three kinds of solutions for the turbulent  $k-\epsilon$  model in the COMSOL software, which are the standard  $k-\epsilon$  turbulence solver, the realizable  $k-\epsilon$  turbulence solver and the low Reynolds number  $k-\epsilon$  turbulence solver. When the average strain rate is large, which may lead to negative normal stress [28,29], for which it is almost impossible to achieve a precise solution, accurate dissipation scales will be barely predicted using the solution for standard  $k-\epsilon$  turbulence. The realizable  $k-\epsilon$  turbulence solver has a higher accuracy and better turbulence consistency in fluid models and is more accurate in simulating flows with large velocity gradients and strong curvatures [30]. The third  $k-\epsilon$  turbulence solver can solve models in all regions up to the wall and is often used to obtain higher precision solutions, but finer mesh and more accurate boundary conditions are needed to improve convergence. When the Reynolds number is high, the boundary layer mesh needs to be very precise, and high computer performance will be required compared with the first two methods. Considering that the gradients of fluid shear rate at the nozzles of the external bit and the nozzles of the internal non-coring bit are large, the realizable  $k-\epsilon$  turbulent solver is selected to improve the accuracy of the bit model in this paper.

Since drilling fluids flowing in a borehole follow conservation laws, including mass conservation, energy conservation, and momentum conservation, the fluids can be regarded as a continuous, incompressible turbulent flow of a single medium [31,32]. Then, the governing equations can be derived.

Firstly, the turbulent kinetic energy,  $k$ , in the transport equation can be expressed as:

$$\rho(\mathbf{u} \cdot \nabla)k = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon. \quad (1)$$

The transport equation of  $\varepsilon$  is:

$$\rho(\mathbf{u} \cdot \nabla)\varepsilon = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_1 \rho S \varepsilon - C_{\varepsilon 2} \frac{\rho \varepsilon^2}{k + \sqrt{\nu \varepsilon}}, \quad (2)$$

in which  $\rho$  is liquid density in  $\text{kg}/\text{m}^3$ ;  $\mathbf{u}$  represents drilling fluid velocities in  $\text{m}/\text{s}$ ;  $\mu$  denotes liquid viscosity in  $\text{Pa} \cdot \text{s}$ ;  $k$  stands for turbulent kinetic energy in  $\text{m}^2/\text{s}^2$ ;  $\mu_T$  is turbulent dynamic viscosity, whose unit is  $\text{Pa} \cdot \text{s}$ ;  $\varepsilon$  represents the turbulent kinetic energy dissipation rate in  $\text{m}^2/\text{s}^3$ ;  $P_k$  represents turbulent kinetic energy in  $\text{kg}/(\text{s}^3 \cdot \text{m})$ ;  $S$  denotes the average strain rate tensor;  $C_{\varepsilon 2}$  is an empirical constant;  $\sigma_k$  and  $\sigma_\varepsilon$  represent Prandtl numbers for the  $k$  equation and  $\varepsilon$  equation, respectively; and  $\nu$  denotes turbulent eddy viscosity in  $\text{N} \cdot \text{S}/\text{m}^2$ , which can be expressed as  $\nu = \frac{\mu_T}{\rho}$ .

In Equation (1), the expression of  $P_k$  is:

$$P_k = \mu_T \nabla \mathbf{u} : (\nabla \mathbf{u} + (\nabla \mathbf{u})^T). \quad (3)$$

In Equation (2), the coefficient  $C_1$  is related to the time-averaged strain rate,  $\tau$ , of the fluid velocity gradient, and its expression is:

$$C_1 = \max \left[ 0.43, \frac{\eta}{5 + \eta} \right], \quad (4)$$

where  $\eta$  is the averaged strain rate tensor modulus, whose expression is  $\eta = S_\varepsilon^k$ .  $S$ , and  $\varepsilon$  can be expressed as [33,34]:

$$\begin{cases} S = \sqrt{2\tau : \tau} \\ \tau = \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \end{cases}. \quad (5)$$

In addition, the turbulent dynamic viscosity,  $\mu_T$ , is:

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}. \quad (6)$$

in which  $C_\mu$  is a variable that changes with the strain rate and is related to the time-averaged strain rate  $\tau$ . Its expression is:

$$C_\mu = \frac{1}{A_0 + A_s U^{(*) \frac{k}{\varepsilon}}}. \quad (7)$$

where  $U^{(*)}$  is internal energy, J, which can be expressed as:

$$U^{(*)} = \sqrt{\tau : \tau + \Omega : \Omega}. \quad (8)$$

$$\Omega = \frac{1}{2} (\nabla \mathbf{u} - (\nabla \mathbf{u})^T). \quad (9)$$

As there is no rotational motion when drilling fluid flows in a borehole, for calculating  $U^{(*)}$ , the second term in the square root in Equation (8) is zero. In Equation (9),  $\Omega$  is the

time-averaged rotational rate tensor, which is derived from the angular velocity reference system. Other parameters are represented as follows:

$$\begin{cases} A_0 = 4.04 \\ A_s = \sqrt{6}\cos\left(\frac{1}{3}\arccos(\sqrt{6}W)\right) \\ W = \frac{2\sqrt{2}\tau:(\tau\cdot\tau)}{|\tau|^3} \end{cases} \quad (10)$$

The main parameters for the modular bit model, along with their respective values, are provided in Table 2.

**Table 2.** Main parameters of the modular bit model.

| Parameters | $\rho$            | $\mu$                 | $\sigma_k$ | $\sigma_\varepsilon$ | $C_{\varepsilon 2}$ |
|------------|-------------------|-----------------------|------------|----------------------|---------------------|
| Values     | $1.0 \times 10^3$ | $1.01 \times 10^{-3}$ | 1.0        | 1.2                  | 1.92                |

The velocity of the drilling fluids flowing upward along the borehole and the pressure loss after drilling fluids have flowed through the bit body have enormous implications for the drilling process, as a sufficiently high velocity can ensure effective cooling of the bit and removal of rock cuttings, but high pressure loss may increase the burden of the mud pumps. Thus, the inlet boundary is set as flow rate boundary with the fully developed mass flow in this paper. For wireline coring drilling with an impregnated diamond bit in geological exploration, the velocity of the drilling fluids flowing upward from the borehole should reach at least 0.5 m/s to 1.5 m/s to carry rock cuttings effectively. To analyze flow field characteristics of drilling fluid flowing in the modular drill bit, a bit was designed with an outer diameter of 216 mm. Thus, the inlet flow rate should be within the range of 300 L/min to 600 L/min, corresponding to a velocity of 0.5 m/s to 1.5 m/s. The boundary condition set for the outlet is specified as a pressure boundary, with a value of 0, which means that the pressure at the outlet is consistent with the ambient pressure. The wall boundaries of the modular bit CFD model are set as fixed no-slip boundaries.

To calculate the simulation model, a segregated stationary solver was adopted, with the turbulent fluid discretization set to P1 + P1 (first order form function to discretize the velocity and pressure fields) and a relative tolerance set to 0.01. Stabilization and acceleration of pseudo time-stepping were selected. The maximum number of iterations, tolerance factor, and residual factor of the solver were set by default.

#### 4. Results and Discussion

A modular drill bit was designed for drilling boreholes with a diameter of 216 mm, and flow field characteristics were analyzed with an inlet flow rate of 300 L/min and outlet pressure at ambient pressure based on the COMSOL software. In this simulation, the diameter of the internal coring bit was 87 mm, and 5 nozzles were opened on the internal non-coring bit.

Figure 3 is a velocity nephogram of the modular drill bit; according to Figure 3a, the drilling fluid in the modular bit for coring drilling flows into the clearance between the external bit and internal bit, and then most of it flows to the borehole bottom through the isolating casing, while a small part of it flows to the bottom of the borehole through the chamber between the isolating casing and internal bit and the passageways between the torque ring and internal bit. After the above two streams of drilling fluid have converged at the borehole bottom, it flows upward through the annulus between the external bit and borehole wall. At the outlet of the isolating casing radial holes, a maximum velocity of 5.07 m/s is generated after drilling fluid collides with the inside wall of the external bit. Then, the velocity decreases when it flows from the chamber between the external bit and the torque ring to the bottom nozzles of the external bit. In the bottom nozzles of the external bit, the velocity increases again and reaches to 4.58 m/s. At the outlet of the nozzles, a vortex is formed, and rocks at the borehole bottom are eroded by the

drilling fluid. Finally, the drilling fluid flows upward at an average velocity of 1.07 m/s. Furthermore, it is observed that the flow velocity near the core is relatively low, signifying effective preservation of the core. For the non-coring bit, shown in Figure 3b, similar laws apply when the drilling fluid flows to the borehole bottom through the isolating casing and nozzles on the external bit. Meanwhile, most of the drilling fluid flows in the center passageway of the internal non-coring bit, and the maximum velocity is generated in the nozzles on the internal non-coring bit with a value of 3.6 m/s; the velocity flowing upward in the annulus of the external bit and borehole can reach to 0.84 m/s.

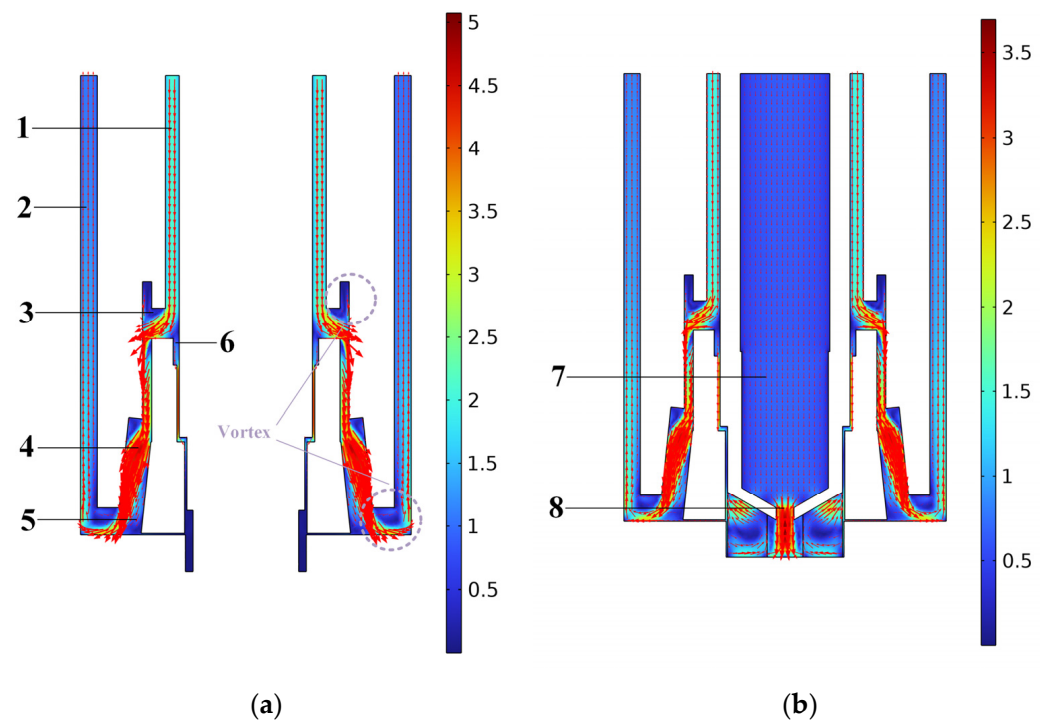


**Figure 3.** Velocity nephogram of the large diameter modular bit: (a) velocity nephogram of the coring drill bit; (b) velocity nephogram of the non-coring drill bit. 1—clearance between the external bit and internal bit; 2—annulus between the external bit and the borehole; 3—chamber between the external bit and torque ring; 4—nozzles on the external bit; 5—water gaps of the external bit; 6—water gaps of the internal bit; 7—center channel of the internal non-coring bit; 8—nozzles of the internal non-coring bit.

Figure 4 illustrates the pressure inside the drill bit. According to this nephogram, pressure decreases gradually as drilling fluid flows through the modular bit. The pressure in the modular bit for coring drilling, shown in Figure 4a, is up to its maximum value of 21,766 Pa at the radial holes of the isolating casing, and the pressure at the core is around 2800 Pa. For the non-coring bit, as shown in Figure 4b, there are different pressure variation laws when drilling fluid is flowing through the external bit and internal bit. The maximum pressure of the external bit occurs at the inlet of the bottom nozzles with a value of 11,249 Pa, and then the pressure decreases rapidly. Meanwhile, the pressure increases sharply from the inlet of the internal bit to its bottom, and the highest pressure occurs at the nozzles of the internal non-coring bit with a value of 12,741 Pa. As the fluid jets out from the bottom nozzles of the internal bit, the pressure gradually decreases, but it experiences a rise at the central region of the borehole bottom, reaching a value of 11,309 Pa.

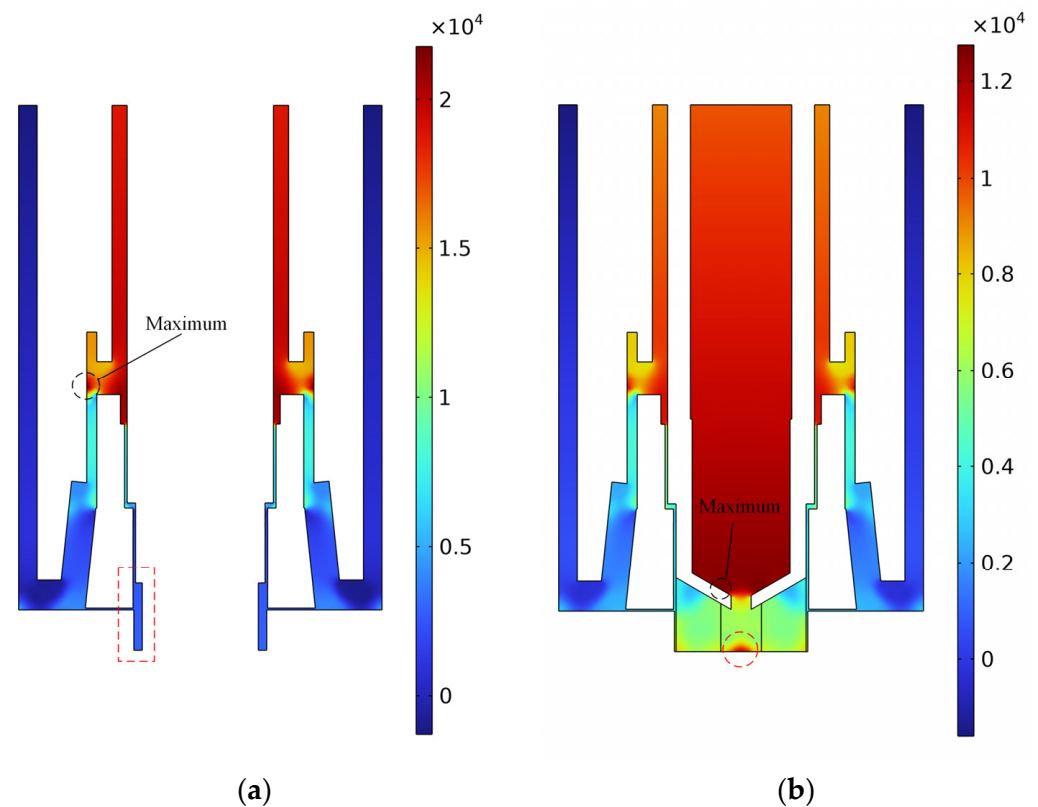


**Figure 4.** Pressure nephogram of the modular bit: (a) pressure nephogram of the coring drill bit; (b) pressure nephogram of the non-coring drill bit.

Figure 5 is a velocity and the pressure nephogram of the bottom section perpendicular to the bit axis when the modular bit drill is in a borehole. As illustrated in Figure 5, once the drilling fluid flows out from the bit, it forms a complete overflow zone in the area of the borehole bottom surface, which is profitable for rock cuttings removal at the borehole bottom and for drill bit cooling. For the coring bit, as in Figure 5a, a dense flow line and high flow velocity are produced in the outlet area of the nozzles on the external drill bit. After flowing out of the nozzles and the clearances between the external bit and internal bit, drilling fluid is mixed and eventually returns upward. In Figure 5c, at the bottom of the borehole, the jet out of the external bit nozzles causes uneven pressure distribution, resulting in a lower pressure zone at every nozzle outlet and two higher pressure zones distributed radially along the drill bit on both sides of the nozzle. As Figure 5b shows, for the non-coring bit, there are two drilling fluid high velocity zones, which are at the outlet of the external drill bit nozzles and the outlet of the internal drill bit nozzles. Around the internal drill bit nozzles, a high pressure zone is generated, while at the nozzles on the external bit low pressure zones are generated, as shown in Figure 5d. With the high pressure at the internal drill bit nozzles, a hydraulic jet will be generated, which helps to improve the capacity of rock cuttings removal and increases rock-free faces so as to raise penetration rates.

In Figure 5a,b, the lines AB and CD are drawn on the coring bit and non-coring bit, respectively. The gradient of velocity on these two lines is illustrated in Figure 6. According to Figure 6a, for the coring bit, the gradient of velocity is symmetrically distributed on line AB relative to the center of the coring bit. There is a trend of initially decreasing, then increasing, and finally decreasing again from the borehole wall to the center of the bit. Figure 6b illustrates that the gradient of velocity at the bottom of the non-coring bit fluctuates, and it is difficult to describe the changing patterns with mathematical expressions. It is worth mentioning that a larger gradient of velocity means a higher

drilling cuttings carrying capacity. In other words, when the drilling fluid flows through the bottom of the coring bit or non-coring bit, rock cuttings can be cleared effectively.

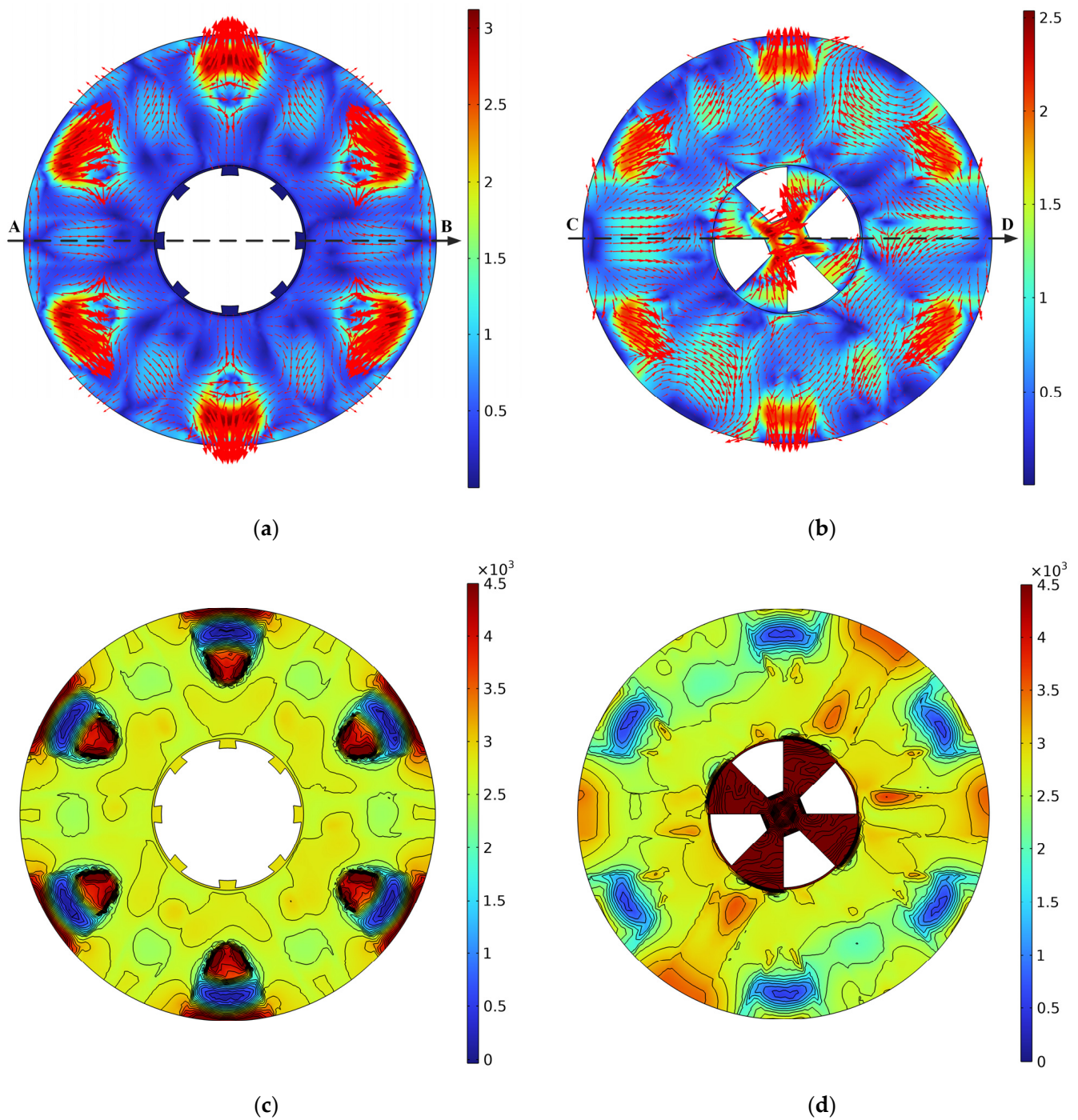


**Figure 5.** Flow velocity and pressure nephogram of the bottom section of the large diameter modular bit: (a) velocity nephogram of the coring drill bit; (b) velocity nephogram of the non-coring drill bit; (c) pressure nephogram of the coring drill bit; (d) pressure nephogram of the non-coring drill bit.

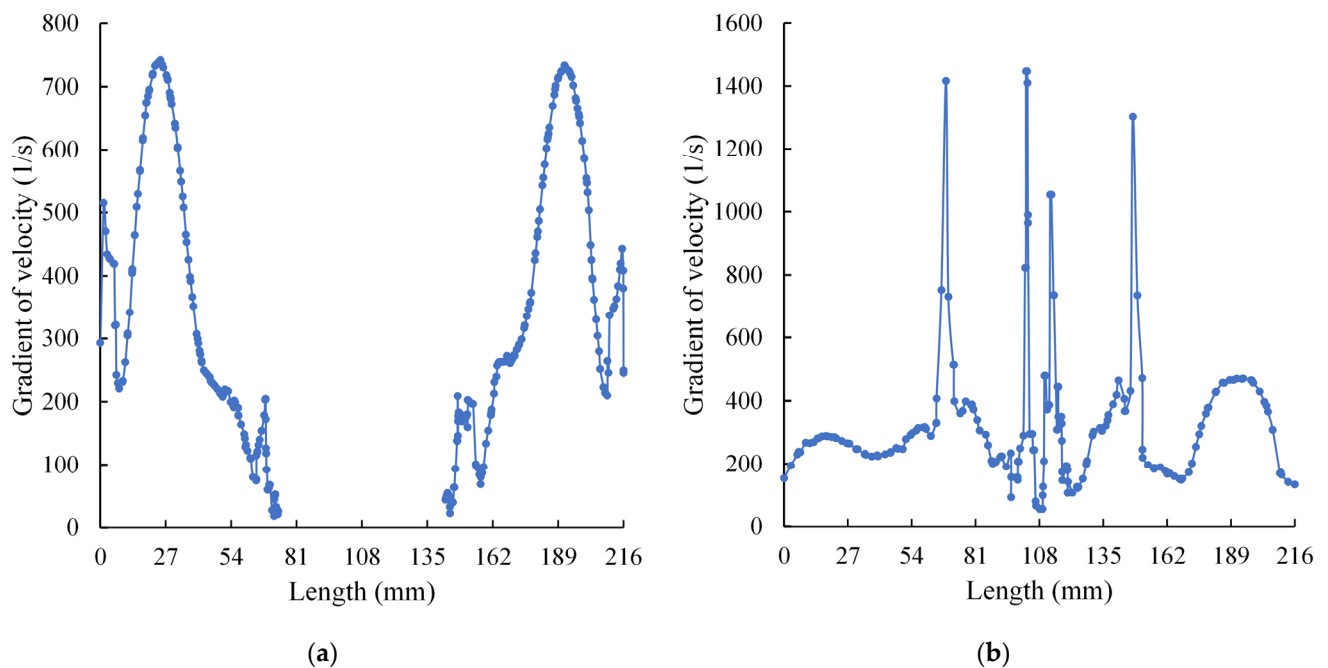


**Figure 6.** Gradient of velocity on line AB and line CD on the bottom surface: (a) gradient of velocity on line AB of the coring drill bit; (b) gradient of velocity on line CD of the non-coring drill bit.

#### 4.1. Flow Characteristics with Different Clearances between the External Bit and Internal Bit for Coring Drilling

The clearance between the external bit and the internal bit is one of the most important structural parameters for the coring bit; it affects the sizes of the internal bit, bit cooling, and rock cuttings removal. When the size of the external drill bit is fixed, increasing the clearance will cause a reduction in the size of the internal bit, and thus small diameter core will be obtained, which may lead to the core-taking volume hardly meeting drilling engineering requirements. Meanwhile, decreasing the clearance will decrease the drilling fluid flow rate and increase pressure loss, which will reduce the bit cooling effect and rock cuttings removal.

A group of coring modular bits with different sizes of internal bits was designed to study flow characteristics when drilling fluid was flowing through them. The outside diameter of the external bit is 216 mm, and the outside diameters for the different sizes of internal bits are 89 mm, 87 mm, 85 mm, 83 mm, and 81 mm. In this case, the clearance between the external bit and internal bit is 8 mm, 9 mm, 10 mm, 11 mm, and 12 mm, respectively. Setting the inlet flow rate at 300 L/min, the velocities and pressures of drilling fluid flowing through the drill bit, which were calculated using the above CFD simulation model, are shown in Figure 7. From the curve, drilling fluid velocities at bit outlet remain largely the same, with an average value at around 0.706 m/s, when increasing the clearance. Meanwhile, with the clearance increasing, the pressure at the bit inlet decreases, and the magnitude of the pressure reduction also decreases, with the slope of the curve slowly becoming flat. As the boundary condition is set to ambient pressure at the bit outlet, which is constant, a large clearance means a large flow section area and low pressure loss. When the inlet flow rate is constant, the cooling effect and rock cuttings removal ability of the drilling fluid flowing through the bit will not be affected. Meanwhile, lower pressure loss can reduce the need for drilling fluid pumping pressure. In this group of simulation analyses, the recommended clearance value is 9 mm or 10 mm, due to the lower pressure loss and larger diameter core obtained.

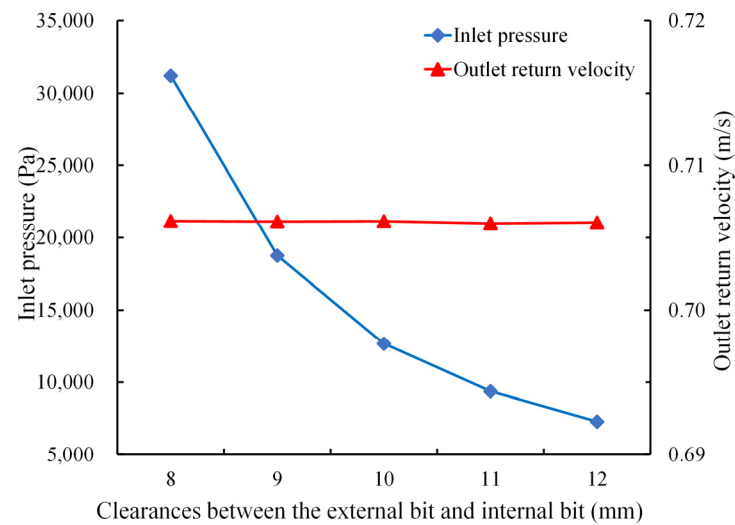


**Figure 7.** Velocity and pressure with different clearances between the external bit and internal bit.

#### 4.2. Influence of the Number of Nozzles at the Bottom of the Internal Bit for Non-Coring Drilling

During non-coring drilling, a water jet will be formed after drilling fluid exits the nozzles of both the external and internal drill bits. When the jet collides with rocks at the bottom of borehole, it can produce impact dynamic pressure and a vortex, which is beneficial for increasing the rock breaking area and rock free surface, thus improving the rock-breaking effect. Therefore, the numbers and arrangement of nozzles on the internal non-coring bit are key factors for bit function. To analyze the flow characteristics of the non-coring modular bit with different nozzles arranged on its internal bit, a group of non-coring modular bits was designed. The outside diameter of the external bit is 216 mm, and the numbers of nozzles on the internal bit are set at 1, 2, 3, 4, and 5, respectively, with a diameter of 12 mm. Figure 8 shows the layout of the nozzles on the internal non-coring bit.

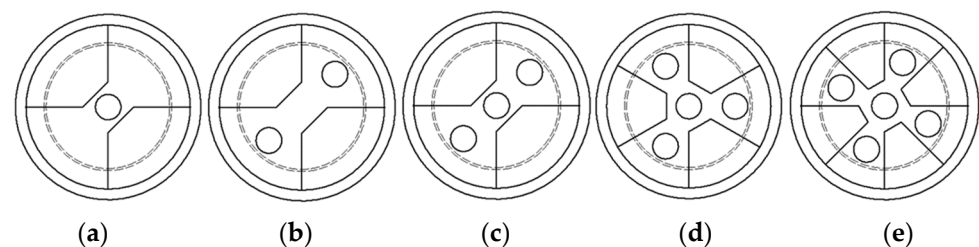


**Figure 8.** Nozzle layout on the internal drill bit for non-coring drilling: (a) one nozzle on the internal non-coring bit; (b) two nozzles on the internal non-coring bit; (c) three nozzles on the internal non-coring bit; (d) four nozzles on the internal non-coring bit; (e) five nozzles on the internal non-coring bit.

With the inlet flow rate set at 300 L/min, the velocity curve and pressure curve are displayed in Figure 9. These results are obtained through the utilization of the CFD simulation model for analyzing drilling fluid dynamics within non-coring bits with different nozzle layouts. According to the curve, drilling fluid velocities at the bit outlet remain largely unchanged, with values at around 0.705 m/s, when increasing the number of the nozzles on the internal non-coring bit. Meanwhile, with the number of nozzles on the internal non-coring bit increasing, the pressure at the bit inlet decreases gradually. Because increasing the number of nozzles on the internal non-coring bit will reduce the size and strength of the teeth on the bit, the teeth on bits will be prone to wear, thus shortening the service life of the bit. In this group of simulations, four nozzles on the internal non-coring bit are recommended, in which case relatively low pressure loss can be achieved.

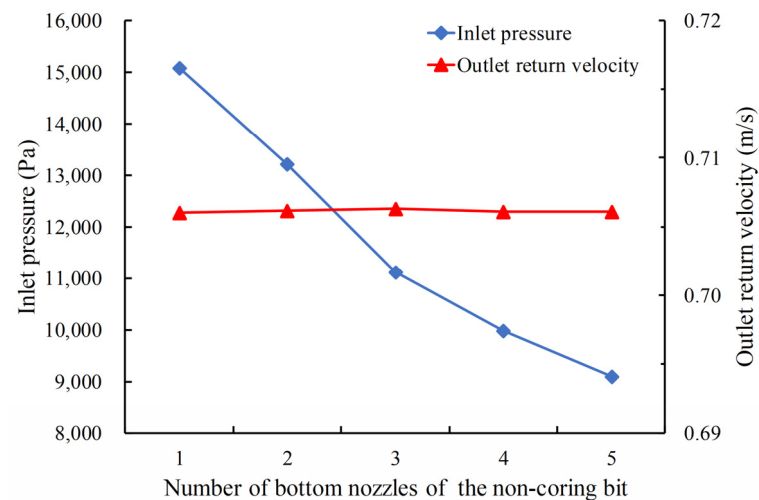
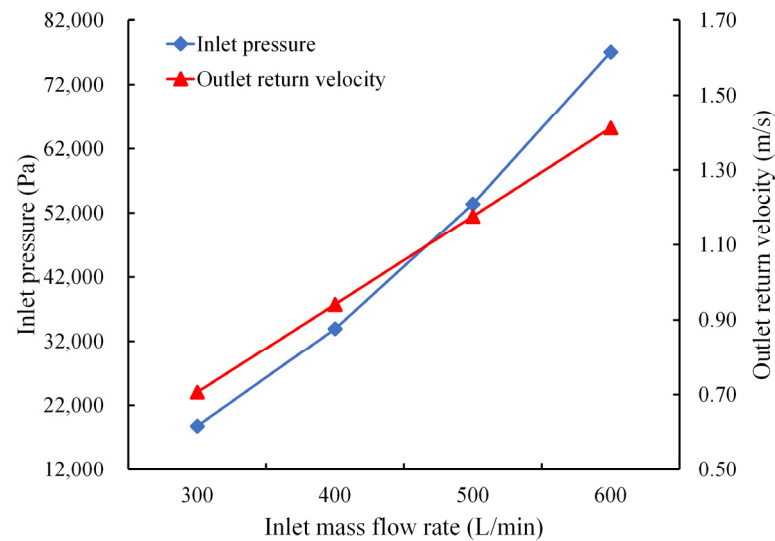


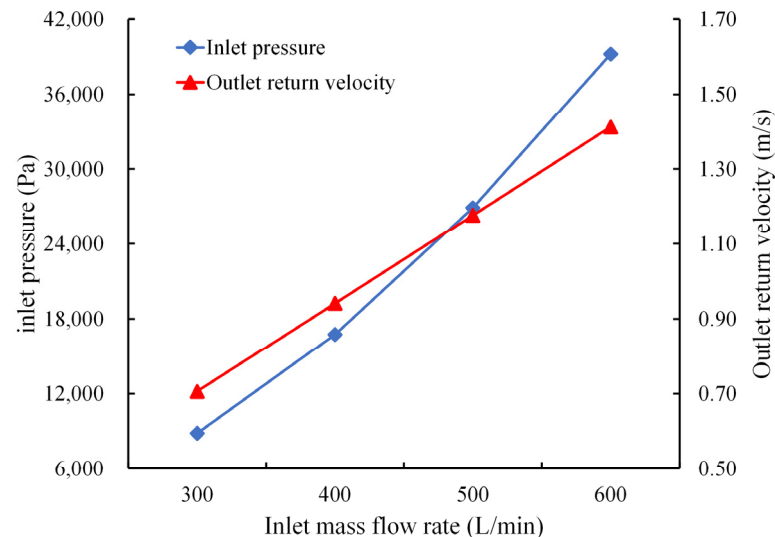
**Figure 9.** Velocities and pressure with different layouts of nozzles on the non-coring bit.

#### 4.3. Flow Characteristics with Different Flow Rate Input

The input flow rate directly determines the flow velocity and pressure of drilling fluid in boreholes. As the flow rate increases, the ability to remove rock debris from the borehole bottom and the effect of bit cooling will be enhanced. Timely removal of rock debris from the borehole bottom significantly affects the drilling process and overall drilling efficiency, as repeated rock crushing and useless energy consumption will be avoided. Meanwhile, circulating flow resistance will also increase correspondingly as flow rate increases, thus increasing the burden of the mud pumps. Furthermore, if the flow rate is too large, it will obviously erode the cores and affect the core recovery rate. Consequently, reasonably optimizing and selecting the drilling fluid input flow rate are very important and necessary in the drilling process. To study the flow characteristics of drilling fluid flowing through drill bits with different input flow rates, a group of simulation analyses was carried out. The inlet flow rates were set to 300, 400, 500, and 600 L/min; the pressure and flow velocity results when drilling fluid flowed through the drill bit are displayed in Figure 10. From these two curves, we find that the pressure and velocity in the coring bit and non-coring bit show similar patterns of change. According to the results, when the input flow rate increases, drilling fluid velocity at the bit outlet increases linearly, and the pressure at the bit inlet increases parabolically. That is to say, increasing drilling fluid flow rate will cause increases in both velocity and pressure, and the pressure rises faster than the velocity. It is recommended to select a small flow rate so that the drilling fluid can carry rock cuttings effectively. For wireline coring drilling, the velocity of the drilling fluids flowing upward from the borehole should reach at least 0.5 m/s to 1.5 m/s to carry rock powder. In the analysis for the coring bit, as Figure 9 shows, the velocity can reach up to 0.706 m/s with the lowest pressure of 18,760 Pa occurring when the inlet flow rate is 300 L/min, which can completely meet the needs of most diamond drilling. For the non-coring bit, when inputting drilling fluid with flow rate of 300 L/min, the drilling fluid's upward velocity can reach up to 0.706 m/s and pressure at the bit inlet can reach 8842 Pa. As there are more rock cuttings produced in non-coring drilling when a borehole is drilled with the same diameter as the coring drilling, a large flow rate needs to be provided to remove rock cuttings effectively. From the perspective of drilling fluid flow characteristics, there needs to be sufficient flow velocity and low pressure loss when drilling fluid flows out of a drill bit. According to these two groups of analyses, it can be concluded that when inputting at the same flow rate, similar velocities and lower pressure loss can be obtained in non-coring drilling compared with the using the coring bit.



(a)



(b)

**Figure 10.** Velocity and pressure with inlet mass flow rate increasing for the large diameter modular drill bit: (a) velocity and pressure of the coring bit; (b) velocity and pressure of the non-coring bit.

## 5. Conclusions

Drilling is one of the most commonly used techniques in hydrogeological exploration and is employed to obtain rock samples and build boreholes. During the drilling process, depending on the specific drilling purpose, it is sometimes necessary to switch between coring drilling and non-coring drilling. To switch between these two drilling methods without lifting the whole set of drilling tools, a modular drill bit is proposed, designed according to the structure of wireline coring tools. The drill bit includes an external bit, an internal coring bit, and an internal non-coring bit. When switching from coring drilling to non-coring drilling, it is necessary just to pull out the inner tube assembly and change the internal coring bit to the internal non-coring bit, without lifting all the drilling tools from the borehole. Flow field characteristics of the modular bit were studied, with factors of inlet mass flow rate, clearance between external bit and internal bit for coring drilling, and layout of the bottom nozzles of the non-coring bit considered.

According to the results, the clearance between the external bit and the internal coring bit has little effect on drilling fluid flow velocity when it flows upward and out of the modular drill bit, while pressure at the bit inlet decreases as the clearance increases. When the outside diameter of the modular bit is 216 mm, the recommended clearance value is 9 mm or 10 mm to obtain lower pressure loss and larger diameter cores. From the analysis of nozzle layout on the non-coring bit, it can be found that velocity of drilling fluid at the outlet of the simulation model remains largely the same, while pressure at the inlet of the simulation model decreases when the number of the nozzles increases. To generate low pressure loss and ensure bit strength, the layout of four nozzles on the internal non-coring bit is recommended for the drill bit with an outside diameter of 216 mm. Based on the result of the inlet flow rate analysis, velocity at the bit outlet increases linearly and the pressure at the bit inlet increases parabolically, as the flow rate increases. With the same input flow rate, similar velocities and lower pressure loss can be obtained in non-coring drilling compared with the using the coring bit, which is suitable for drilling conditions when more cuttings are produced in non-coring drilling than in coring drilling for a borehole drilled with the same diameter.

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