

Article

Numerical Investigation of Horizontal Wellbore Hole Cleaning with a Flexible Drill Pipe Using the CFD–DEM

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Abstract

Efficient cutting transport is crucial in challenging drilling environments such as ultra-short-radius horizontal wells. Flexible drill pipes, designed for complex wellbore geometries, offer a potential solution. However, the cutting transport behavior within them remains poorly understood. To improve wellbore cleaning and drilling efficiency, this study investigates the underlying transport mechanisms. The investigation employs a coupled CFD-DEM approach to model cutting transport in flexible drill pipes. This method combines fluid dynamics and particle motion simulations to analyze the interaction between drilling fluid and cuttings, evaluating the impact of factors such as rotational speed, flow rate, and fluid properties on cleaning efficiency. The results indicate that increasing the flow rate at a constant rotational speed significantly reduces the cutting concentration. Nevertheless, beyond a critical flow rate of 1.5 m/s, further increases yield diminishing returns in cleaning efficiency due to transport capacity saturation. In contrast, increasing the rotational speed at a fixed flow rate of 1.42 m/s has a less pronounced effect on cutting transport and increases frictional torque, thereby reducing energy efficiency. Higher rotational speeds primarily enhance the suspension of fine cuttings, with minimal impact on larger particles. Additionally, the rheological properties of the drilling fluid play a key role. A higher flow behavior index increases viscosity near the wellbore, improving transport performance. Conversely, a higher consistency index enhances the fluid's carrying capacity but increases annular pressure drop, which imposes greater demands on pump capacity. Thus, optimal drilling performance requires balancing pressure losses and cleaning efficiency through comprehensive parameter optimization.

Keywords: flexible drill pipe; CFD-DEM coupling simulation; hole cleaning; cuttings transport; rheological properties



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1. Introduction

Petroleum resources continue to play indispensable roles in ensuring global energy supply and socioeconomic development [1–3]. Since conventional oil and gas reservoirs are being depleted, the development of efficient technologies for the remaining oil has become crucial for ensuring energy security [4,5]. In this context, ultra-short-radius drilling technology is considered suitable for hydrocarbon reservoirs with difficulties in energy

production, such as the remaining oil reservoirs, reservoirs with thin layers, and reservoirs with low-permeability formations [6]. Unlike conventional vertical well technologies, this technology enables the sidetracking of multiple horizontal branches from existing wellbores with extremely short radii of curvature, facilitating rapid build-up in certain sections and precise lateral drilling along the reservoir [7,8]. These phenomena significantly increase the contact area between the wellbore and the reservoir, thereby effectively increasing recovery rates and single-well productivity. This technology is potentially applicable to the tapping of old wells, serving as an efficient and economical development method [9–11].

As shown in Figure 1a, ultra-short-radius drilling technologies for horizontal wells require the wellbore direction to transition from vertical to horizontal within an extremely short distance. The radius of curvature typically ranges from 1 to 6 m, which is considerably smaller than that of conventional horizontal wells [12,13]. This restriction imposes stringent requirements on drilling tools. In these small-radius wellbores, owing to their high rigidity, conventional drill pipes cannot pass through sharply curved sections and are prone to excessive friction, severe buckling, and even structural failure [13,14]. These characteristics result in inefficient drilling, inability to position tools accurately, or downhole accidents [15,16]. Therefore, to ensure safe and efficient drilling in ultra-short-radius wellbores, it is essential to employ flexible drilling tools with high flexibility, high fatigue resistance, and effective power transmission capabilities [12]. These tools are designed to withstand extreme bending conditions while ensuring steering and drilling accuracy, as shown in Figure 1b. The classification of horizontal well technologies is presented in Table 1.

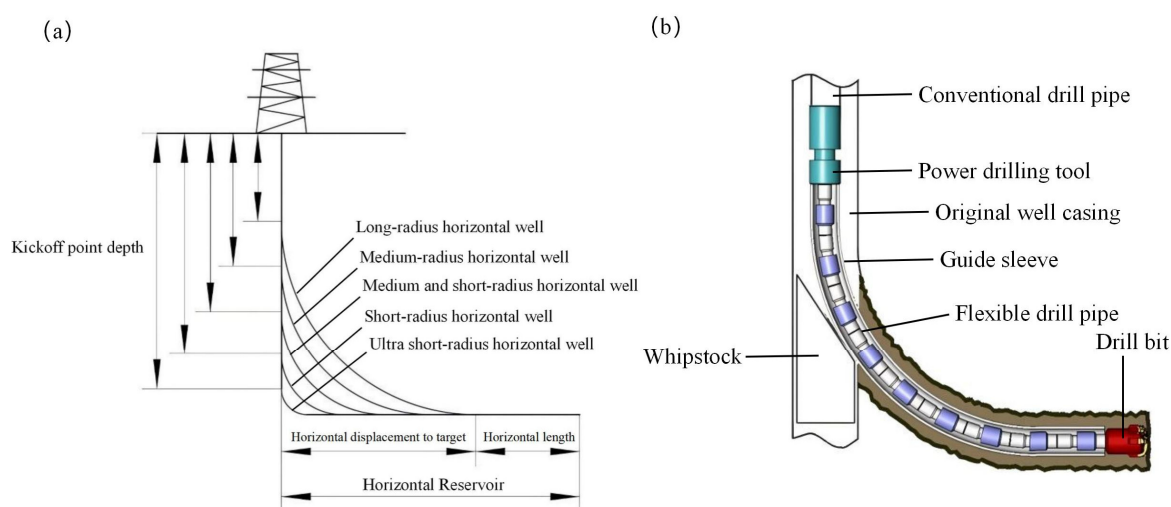


Figure 1. Schematic illustrations of ultra-short-radius drilling technologies for horizontal wells and flexible drill pipes. (a) Comparison charts of various types of horizontal wells; (b) Schematic illustration of the guided high-build-rate drilling tool assembly.

Table 1. Classification and Comparative Analysis of Horizontal Well Technologies.

Horizontal Well Category	Build-Up Rate (°)	Wellbore Curvature Radius	Length
Long-radius	2~<6	285~<860	≥300
Medium-radius	6~<20	85~<285	≤1000
Medium- and short-radius	20~<60	30~<85	≤300
Short-radius	60~<300	6~<30	≤300
Ultra-short-radius	≥300	1~<6	≤100

Ultra-short-radius drilling imposes increased demands on drilling tool flexibility and wellbore cleaning capacity. Conventional rigid drill pipes struggle to adapt to wellbores with small radii of curvature [17], whereas flexible drill pipes, leveraging their multi-joint structures and dynamic deformation capabilities, can move flexibly within ultra-short-radius wellbores, providing technical support for drilling under complex geological conditions [18,19]. However, while their complex structures increase flexibility, they introduce challenges. The first guided ultra-short-radius drilling-based horizontal well implemented in the Shengli Oilfield in 2019 exhibited a radius of curvature of 3 m and a wellbore diameter ranging from 114 to 118 mm. Field tests revealed that when the flexible drilling tool advanced more than 30 m into the horizontal section, complex conditions emerged, including high friction torque, elevated drilling pump pressure, and insufficient cutting return despite the extended drilling process. These characteristics led to severe wear of the flexible drilling tool and even tool failure, preventing the horizontal section from reaching its intended extension length and constraining the technical maturity of the research outcomes. As a result, large-scale application remains challenging. The root cause is the numerous joints and internal channel steps of the flexible drill pipe [20]. When the drilling fluid carries cuttings upward through the annulus between the flexible drill pipe and the wellbore, the flow velocity becomes uneven because of the connection geometry, spatial configuration, and rotation of the flexible drilling tool. Cuttings settle in low-velocity regions, forming a cutting bed, which further increases friction between the flexible drill pipe and the wellbore and thus hinders wellbore extension [21]. These phenomena highlight the inadequate wellbore cleaning efficiency in horizontal wells developed from ultra-short-radius drilling, underscoring the urgent need for optimization. A review of current research on cutting transport mechanisms in wellbores reveals that scholars have predominantly focused on traditional rigid drilling tools, performing limited analyses on the cutting transport behaviors of flexible drill pipes specifically [22,23].

Understanding the dynamics of the wellbore and the behavior of cuttings while drilling is complex by nature; therefore, companies attempt to utilize the advantages of modeling or numerical simulations to predict and mitigate the impact of this issue by implementing proactive solutions in advance [24–26]. Numerical simulation methods have become essential tools for studying drilling processes in horizontal wells because of their relatively low computational costs, abilities to replicate downhole conditions, and strong parametric analysis capabilities [27,28]. Currently, the computational fluid dynamics (CFD)–discrete element method (DEM) approach has been successfully applied in areas such as cutting transport and wellbore cleaning [27,29–31]. Shao et al. [29] used a coupled CFD–DEM approach to investigate the annular transport behaviors of nonspherical large cuttings in coalbed methane (CBM) drilling. The authors employed a multi-sphere discrete element method to model cubic, flaky, and spherical particles. They reported that under equivalent volume conditions, particle shape significantly influences transport efficiency: spherical particles perform best, followed by flaky particles, with cubic particles being the least efficient. On the basis of the CFD–DEM, Yan et al. [30] innovatively proposed and numerically studied the impact of a four-lobed helical drill pipe on wellbore cleaning efficiency in horizontal wells. The researchers reported that the four-lobed design induces strong swirling flow through geometric curvature, significantly enhancing the cutting transport ability compared with that of conventional circular drill pipes. This improvement reduces the concentration of annular cuttings under solid–liquid two-phase conditions, with the cleaning efficiency improving as the drill pipe eccentricity increases. Sun et al. [32] applied CFD–DEM to numerically simulate cutting transport patterns accompanied by drill pipe rotation in extended-reach horizontal wells. The scholars analyzed the effects of transport velocity, drill pipe rotational speed, and eccentricity on cutting flow patterns in

the wellbore. Their results indicated that transport velocity is a key factor in determining flow pattern transition and annular pressure drop characteristics. A critical velocity (approximately 3 m/s) exists: below this velocity, the dimensionless pressure drop decreases with increasing velocity, whereas above it, the pressure drop increases—a phenomenon closely related to changes in cutting bed thickness and energy consumption. To date, no systematic numerical simulation studies on cutting transport in flexible drill pipes have been reported in the literature.

In this study, to address issues such as the high friction and low cutting evacuation efficiency observed in field applications of flexible drill pipes, the CFD–DEM is employed to simulate the influence of flexible drill pipes on cutting transport behavior. The aim is to clarify the effects of the circulation rate, drill pipe rotational speed, and drilling fluid rheological properties on the transport of cuttings during actual drilling operations. By optimizing the drilling parameters and improving the drilling fluid properties, the wellbore cleaning efficiency can be increased, ultimately extending the reach of ultrashort-radius horizontal wells while achieving technological breakthroughs.

2. Coupled CFD–DEM Methodology

In this study, the fluid phase is computed using ANSYS Fluent 2024R1 software, which is based on the finite volume method, to solve the incompressible Navier–Stokes equations and obtain flow field information. The motion and collision behaviors of the particle phase are simulated using Rocky DEM 2024R1 software, which is specialized for granular system simulations and relies on the DEM to accurately resolve the forces and motion trajectories of each cutting particle. In the fluid–solid interaction model, the interplay between CFD and the DEM is achieved through the exchange of mass, momentum, and energy. CFD is coupled with the DEM to enable detailed simulation of the interactions between continuous fluids and discrete particles in solid–liquid two-phase flow. The CFD–DEM coupling framework is shown in Figure 2. This section is focused on the equations governing solid–liquid two-phase flow and the coupling mechanisms.

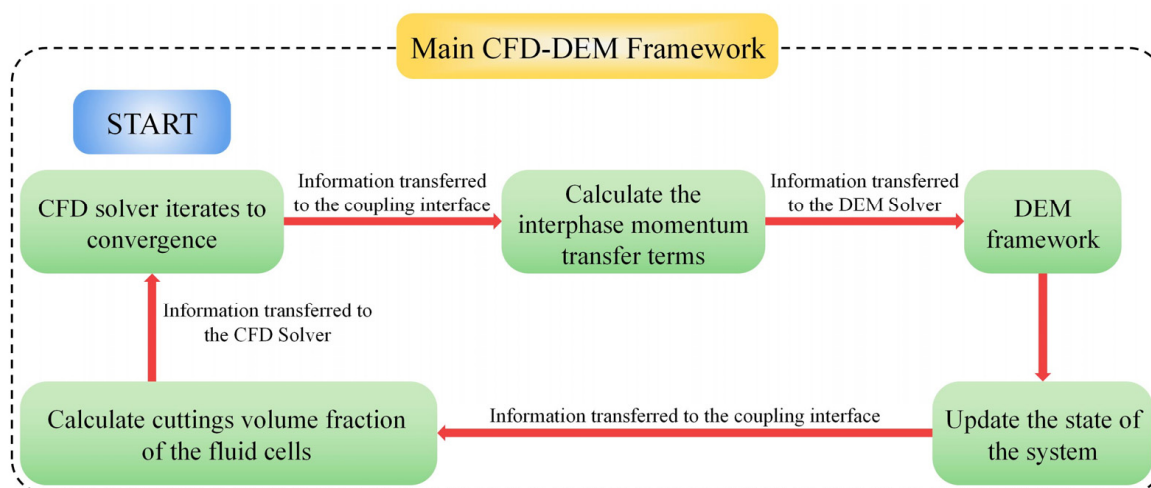


Figure 2. CFD–DEM coupling framework.

2.1. Solid Phase

2.1.1. Governing Equations for the Solid Phase

The DEM precisely describes the dynamic behaviors of discrete phases by tracking the motion of individual particles and their interactions. The governing equations for the discrete phase are based on Newton’s laws of motion, encompassing models for particle

translation, rotation, and contact mechanics. The translational motion of an individual particle is governed by Newton's second law:

$$m_p \frac{dv_p}{dt} = \sum F_{c,pq} + F_{pf,p} + m_p g \left(1 - \frac{\rho_f}{\rho_p}\right) \quad (1)$$

where m_p represents the mass of particle p ; v_p represents the velocity vector of particle p ; $F_{c,pq}$ represents the contact forces between the particles and the walls (e.g., the Hertz–Mindlin normal and tangential forces); $F_{pf,p}$ represents the fluid–particle interaction forces; g represents the gravitational acceleration; and ρ_f and ρ_p represent the fluid density and particle density, respectively.

The rotational motion of particles is governed by the angular momentum conservation equation:

$$I_p \frac{d\omega_p}{dt} = \sum (T_{t,pq} + T_{r,pq}) + T_{f,p} \quad (2)$$

where I_p is the moment of inertia of particle p ; ω_p is the angular velocity vector of particle p ; $T_{t,pq}$ and $T_{r,pq}$ are the torque due to the tangential contact force and rolling friction torque, respectively; and $T_{f,p}$ is the torque caused by the fluid.

2.1.2. Contact Forces Between Particles

The contact forces during the transport of cuttings are typically divided into three types: cutting-to-cutting, cutting-to-drill pipe, and cutting-to-wellbore.

The contact force exerted on cutting particles p by cutting particles q can be expressed as follows [33]:

$$F_{c,q}^p = F_{n,pq} + F_{n,pq}^d + F_{t,pq} + F_{t,pq}^d \quad (3)$$

where $F_{n,pq}$, $F_{t,pq}$, $F_{n,pq}^d$, and $F_{t,pq}^d$ denote the normal elastic force, tangential elastic force, normal damping force, and tangential damping force, respectively. On the basis of elastic contact mechanics, the nonlinear relationship between the normal force F_n and the normal overlap δ_n can be expressed as follows:

$$F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^3 \quad (4)$$

where E^* is the equivalent elastic modulus ($E^* = \left[\frac{(1-\nu_p^2)}{E_p} + \frac{(1-\nu_q^2)}{E_q} \right]^{-1}$) and R^* is the equivalent radius $R^* = \left[\frac{2}{d_p} + \frac{2}{d_q} \right]^{-1}$. Here, E_p , ν_p , and d_p and E_q , ν_q , and d_q denote Young's modulus, Poisson's ratio, and the diameter of particles p and q , respectively. The normal damping force $F_{n,pq}^d$ can be expressed as follows [33]:

$$F_{n,pq}^d = -2\sqrt{\frac{5}{6}} \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}} \sqrt{S_{n,pq} m^*} v_{n,pq} \quad (5)$$

where m^* is the equivalent cutting mass ($m^* = \left[\frac{2}{m_p} + \frac{2}{m_q} \right]^{-1}$); m_p and m_q are the masses of individual particles in the contact pair; $S_{n,pq}$ is the normal stiffness ($S_{n,pq} = 2E^* \sqrt{R^* \delta_{n,pq}}$); $v_{n,pq}$ is the normal component of the relative velocity at the contact point; and e is the restitution coefficient. The tangential contact force $F_{t,pq}$ can be expressed as follows [33]:

$$F_{t,pq} = \begin{cases} -\delta_{t,pq} S_{t,pq} & |F_{t,pq}| < \mu_s |F_{n,pq}| \\ \mu_s |F_{n,pq}| \frac{v_{t,pq}}{|v_{t,pq}|} & |F_{t,pq}| \geq \mu_s |F_{n,pq}| \end{cases} \quad (6)$$

The torques generated by rotational motion during cutting migration are defined as follows:

The torque due to the tangential forces resulting from the collision of cutting particles q against particle p is given as follows:

$$T_{t,q}^P = r_{pq} \times (F_{t,pq} + F_{t,pq}^d) \quad (7)$$

The friction torque resisting the rolling of particle p induced by the collision with particle q is expressed as follows:

$$T_{r,q}^P = -\mu_r |r_{pq}| |F_{n,pq}| \frac{\omega_{pq}}{|\omega_{pq}|} \quad (8)$$

where r_{pq} is the vector from the centroid of cutting particle p to the contact point; μ_r is the rolling friction coefficient; and ω_{pq} is the relative angular velocity of particle p with respect to particle q . $T_{t,q}^P$ and $T_{r,q}^P$ correspond to the torque due to the tangential contact force and rolling friction torque, respectively.

When particles collide with the wellbore wall or drill pipe, the contact forces are computed identically to those of interparticle collisions. In such scenarios, the wellbore wall velocity is treated as zero and modeled as a particle with infinite diameter and mass.

2.2. Fluid Phase

The flow of the drilling fluid is governed by the Navier–Stokes equations. Within the Eulerian framework, the continuity equation and momentum equation for the liquid phase are established as follows:

Continuity equation:

$$\frac{\partial(\varepsilon_l \rho_l)}{\partial t} + \frac{\partial(\varepsilon_l \rho_l u_j)}{\partial x_j} = 0 \quad (9)$$

Momentum equation:

$$\frac{\partial(\varepsilon_l \rho_l u_i)}{\partial t} + \frac{\partial(\varepsilon_l \rho_l u_j u_i)}{\partial x_j} = -\varepsilon_l \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} (\varepsilon_l \tau_{ji}) - \beta(u_i - v_i) + \varepsilon_l \rho_l g \quad (10)$$

where ρ_l is the liquid density (kg/m^3) and τ_{ji} is the viscous stress tensor. The subscript i refers to the coordinate direction, and j refers to the Einstein summation index. The viscous stress tensor is defined as follows:

$$\tau_{ji} = \left(\mu + \mu_t \right) \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (11)$$

where μ is the dynamic viscosity coefficient of the liquid and μ_t is the turbulent viscosity coefficient, which is calculated as $\mu_t = \rho_l c_\mu k^2 / \varepsilon$.

$$\frac{\partial(\varepsilon_i \rho_i k)}{\partial t} + \frac{\partial(\varepsilon_i \rho_i u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\varepsilon_i \left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \varepsilon_i \mu_t \frac{\partial u_i}{\partial x_j} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \varepsilon_i \rho_i \varepsilon \quad (12)$$

$$\frac{\partial(\varepsilon_t \rho_t \varepsilon)}{\partial t} + \frac{\partial(\varepsilon_t \rho_t u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\varepsilon_t \left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon_t c_t \varepsilon}{k} \mu_t \frac{\partial u_i}{\partial x_j} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \varepsilon_t c_2 \rho_t \frac{\varepsilon^2}{k} \quad (13)$$

2.3. Solid–Liquid Coupling

When relative motion occurs between the drilling fluid and cuttings, the cutting particles are subjected to a fluid drag force, which acts in the same direction as the relative

motion of the fluid with respect to the particles. The drag force is calculated using the following formula:

$$F_{d,i} = V_p \frac{\beta}{1 - \varepsilon_g} (u - v) \quad (14)$$

where V_p is the volume of particle p , $V_p = \frac{4\pi r^3}{3}$; β is the drag coefficient; g is the porosity; and u and v are the liquid velocity and the average velocity of all the particles within a single grid, respectively, in m/s. Here, the formula provided by the Gidaspow model is used for calculation, yielding the following equation:

$$\beta = \begin{cases} \frac{\mu(1-\varepsilon_l)}{d_p^2 \varepsilon_l} [150(1 - \varepsilon_l) + 1.75 \text{Re}_p] & (\varepsilon_l \leq 0.8) \\ \frac{3}{4} C_D \frac{\mu(1-\varepsilon_l)}{d_p^2} \varepsilon_l^{-2.65} \text{Re}_p & (\varepsilon_l > 0.8) \end{cases} \quad (15)$$

$$C_D = \begin{cases} \frac{24(1+0.15 \text{Re}_p^{0.687})}{\text{Re}_p} & (\text{Re}_p \leq 1000) \\ 0.44 & (\text{Re}_p > 1000) \end{cases} \quad (16)$$

The Reynolds number Re is given as follows:

$$\text{Re}_p = \frac{\rho_l \varepsilon_l d_p |u - v|}{\mu} \quad (17)$$

where d_p is the particle diameter (m), u is the fluid velocity (m/s), v is the particle velocity (m/s), ε_l is the porosity, and μ is the fluid shear viscosity.

The lift forces include shear-induced lift (Saffman force) and rotation-induced lift (Magnus force), both of which are perpendicular to the direction of the relative velocity between the cuttings and the fluid. The shear-induced lift (Saffman force) acting on particle p is given as follows:

$$F_S = C_{LS} \frac{\rho_f \pi}{8} d_p^3 [u_f - u_p \times \omega_f] \quad (18)$$

where ω_f represents the curl of the fluid velocity ($\omega_f = \nabla \times u_f$). The shear-induced lift force is expressed as:

$$C_{LS} = \frac{4.1126}{\text{Re}_s^{0.5}} f(\text{Re}_{HB}, \text{Re}_s) \quad (19)$$

$$f(\text{Re}_{HB}, \text{Re}_s) = \begin{cases} (1 - 0.3314\beta^{0.5})e^{-\frac{\text{Re}_{HB}}{10}} + 0.3314\beta^{0.5} & \text{Re}_{HB} \leq 40 \\ 0.0524(\beta \text{Re}_{HB})^{0.5} & \text{Re}_{HB} > 40 \end{cases} \quad (20)$$

where $\beta = 0.5 \text{Re}_s / \text{Re}_{HB}$ ($0.005 < \beta < 0.4$), and the Reynolds number for shear flow is defined as $\text{Re}_s = \rho_f d_p^2 \omega_f / \mu$.

The rotation-induced lift force (magnus force) acting on particle p can be obtained as follows:

$$F_M = C_{LM} \frac{\rho_f \pi}{8} d_p^3 |u_f - u_p| \frac{[\Omega \times (u_f - u_p)]}{|\Omega|} \quad (21)$$

where the rotation-induced lift coefficient C_{LM} can be expressed as follows:

$$C_{LM} = 0.45 + \left(\frac{\text{Re}_r}{\text{Re}_{HB}} - 0.454 \right) e^{-0.5684 \text{Re}_r^{0.4} \text{Re}_{HB}^{0.3}} \quad (22)$$

In addition to the lift forces, the particles are subjected to a pressure gradient force, which is induced by the pressure gradient of the circulating drilling fluid. This force can be expressed as follows:

$$F_P = -V_p \nabla P \quad (23)$$

where V_p denotes the volume of cutting particles p , and ∇P represents the static pressure gradient of the fluid phase at the particle location.

2.4. Applied Assumptions of the Model

- (1) A 10-segment drill pipe was used to simulate a full-length drill pipe.
- (2) The model is designed only for the horizontal section.
- (3) The drilling fluid is an incompressible non-Newtonian liquid.
- (4) Isothermal system.

3. Calculation Model and Conditions for Horizontal Flexible Drill Pipes

3.1. Model Geometry and Conditions

The physical simulation model established in this study is shown in Figure 3. The computational domain comprises an annular space formed by the wellbore and a flexible drill pipe, with an inner wellbore diameter of 130 mm and an outer drill pipe diameter of 100 mm. The inclination angle is set to 90° , corresponding to the conditions of a horizontal well. In the simulation, cutting particles are treated as a discrete phase with a density of 2666 kg/m^3 and a Poisson's ratio of 0.3. Irregular particles of varying diameters are used to represent cuttings, simulating the realistic shape of actual drilled fragments. This approach effectively captures the morphological characteristics of cuttings during real drilling operations, thereby increasing the rationality and accuracy of the simulation. As shown in Figure 4, the cuttings are treated as rock particles with a density of 2666 kg/m^3 and the following size distribution: 20% being 3 mm in size, 65% being 4 mm in size, and 15% being 5 mm in size. Under experimental conditions, when the system reaches a steady state, the number of cutting particles in the entire annular domain can exceed several million. Owing to the substantial computational load per time step, the total simulation time increases significantly. To reduce computational costs and improve simulation efficiency, the model is reasonably simplified. This model includes ten sections of articulated flexible drill pipe, each with a length of 0.19 m, resulting in a theoretical total length of 1.9 m. However, owing to the dynamic bending of the drill pipe, its actual effective length is reduced to 1.83 m.

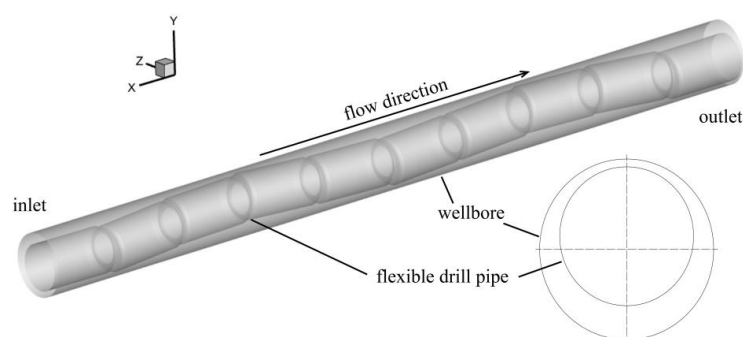


Figure 3. Schematic illustration of the flexible drill pipe.

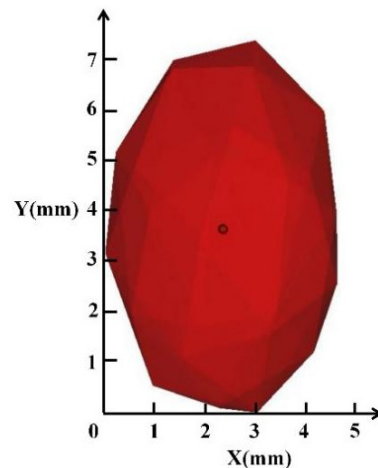


Figure 4. Schematic illustration of cutting particles.

Furthermore, the flexible drill pipe is not perfectly centered along the wellbore axis, and it exhibits a certain degree of eccentricity. In the hydrodynamic simulation, velocity inlet and pressure outlet boundary conditions are selected to meet the requirements of the computational model. To simulate the rotation of the drill pipe, a sliding mesh technique is employed. The fluid domain is divided into two layers using hexagonal meshes, with a total of 376,949 cells and an average mesh quality of 0.91, as shown in Figure 5. In Figure 5, inlet 1 denotes the inner fluid domain, while inlet 2 refers to the outer fluid domain. The inner layer constitutes the rotating fluid domain, where the mesh rotates synchronously with the drill pipe to simulate circumferential flow along the drill pipe surface and capture the effects of rotation on cutting transport. The outer layer represents the stationary fluid domain, which remains fixed along the wellbore wall. Data exchange between the two layers is achieved through an interface, ensuring continuity of velocity, pressure, and other parameters at the boundary between the rotating and stationary meshes. To increase the computational accuracy, boundary layer refinement is applied to the mesh near the drill pipe surface and wellbore wall. Table 2 outlines the physical and rheological properties of the drilling fluid and cuttings used in the numerical simulation, while Table 3 provides the geometric dimensions and simulation parameters adopted in this study.

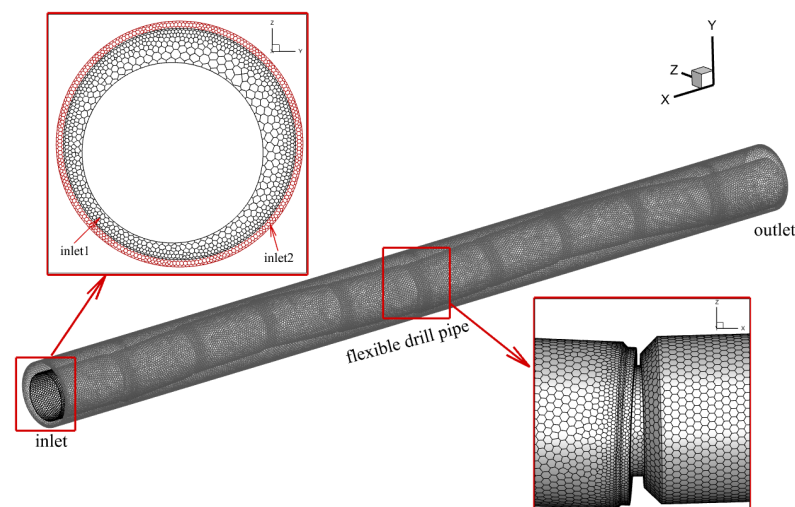


Figure 5. Computational grid of the flexible drill pipe.

Table 2. Physical and rheological properties of the drilling fluid and cuttings used in the numerical simulations.

Category	Parameter	Symbol	Values	Units
Fluid	Drilling Fluid density	ρ_f	1150	kg/m ³
	Flow behavior index	n	0.4, 0.5, 0.6	-
	Consistency coefficient	k	0.3, 0.6, 0.9, 1.2	Pa·s ⁿ
Cuttings	Cutting density	ρ_c	2666	kg/m ³
	Cutting diameter	D_c	3, 4, 5	mm
	Young's modular	E	1×10^8	N/m ²
	Poisson ratio	ν	0.3	-
	Static friction	μ_s	0.8	-
	Dynamic friction	μ_k	0.8	-
	Coefficient of restitution	e	0.5	-

Table 3. Geometric parameters and operating conditions in the numerical simulation.

Category	Parameter	Symbol	Values	Units
Geometry	Wellbore diameter	D_1	130	mm
	Angle of inclination	θ	90	°
	Wellbore length	L	1.83	m
	Drill pipe diameter	D_0	100	mm
Operational	Drill pipe rotational speed	n_0	10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110	rpm
	Drilling fluid circulation velocity	v	0.6, 0.75, 0.9, 1.05, 1.2, 1.35, 1.5, 1.65, 1.8, 1.95	m/s

In this study, the finite volume method coupled with the phase coupled SIMPLE algorithm is employed to discretize the governing equations. A first-order implicit time integration method is adopted to solve the governing equations. For the momentum, volume fraction, and turbulence equations, a first-order upwind scheme is used. Simultaneously, an implicit time integration method is applied to solve the equations of motion for discrete particles in the DEM simulation. To ensure computational stability and accuracy, the numerical simulation incorporates automatic time stepping in Rocky 2024R1 software, enabling efficient and precise simulation results.

3.2. Grid Independence Verification

To ensure the accuracy of the transient numerical simulation results and minimize the influence of grid density on computational outcomes, a systematic grid independence study was conducted in this work.

3.2.1. Grid Scheme Design

Based on the established geometric model, three grid schemes with varying densities were designed for comparative analysis, as presented in Table 4.

Three distinct mesh levels were constructed to balance computational efficiency and accuracy. The coarse mesh, characterized by a relatively large global element size, served as the baseline for preliminary calculations and rapid design evaluation. Building upon this, the medium mesh was generated by systematically refining critical regions, including the interfaces between rotating and static components, the drill string surface, and the boundary layers near the wellbore wall. Finally, the fine mesh was produced by applying

further global refinement to the medium mesh, providing a high-resolution reference solution for assessing the accuracy of the results obtained on the coarser grids.

Table 4. Grid Division Scheme.

Grid Level	Number of Grids	Local Mesh Refinement in the Annular Region
Coarse grid	104,169	Basic Mesh Refinement
Middle grid	376,949	Local mesh refinement at interfaces and other critical regions
Fine grid	683,905	Global High-Resolution Refinement

3.2.2. Verification Parameters and Monitoring Methodologies

For grid independence verification in transient flow simulations, it is essential to focus on physical quantities that characterize the dynamic behavior of the flow field. In this study, the following parameters were selected for quantitative assessment:

Time-averaged pressure drop ($\Delta\bar{P}$): The average pressure difference between the inlet and outlet of the computational domain was monitored to verify the convergence of global flow resistance.

Standard deviation of pressure fluctuations (σ_p): Pressure transient signals were collected at five monitoring points located ahead of, behind, and at the narrowest gap along the whirling path of the flexible drill string in the annulus. The standard deviation of these signals was calculated as a key metric to quantify the intensity of pressure fluctuations.

Since one of the objectives of this study is to accurately capture the global pressure waves and energy transmission induced by the revolution of the drill string, the convergence of pressure fluctuations was adopted as the primary criterion for grid independence.

3.2.3. Convergence Criterion

Three mesh configurations were established in this study: a coarse mesh (approximately 100,000 cells), a medium mesh (approximately 400,000 cells), and a fine mesh (approximately 700,000 cells). The sensitivity of the mesh was evaluated by comparing the computed results of key flow parameters across the different mesh densities.

The selected metrics for verification were the time-averaged pressure drop of the flow field and the standard deviation of pressure fluctuations at five characteristic monitoring points (P1 to P5). The rate of change for each parameter between the medium and fine meshes was calculated using the following formula:

$$\varepsilon = \left| \frac{\phi_{\text{median}} - \phi_{\text{fine}}}{\phi_{\text{fine}}} \right| \times 100\% \quad (24)$$

where ϕ is used to denote any physical quantity under comparison.

The computational results presented in Table 5 show that the relative change in time-averaged pressure drop is only 0.90%, indicating that the global flow characteristics have reached mesh independence. For local pressure fluctuations, the majority of monitoring points exhibit a variation rate below 3.0% (P4: 2.99%, P5: 2.16%), with P1 and P3 showing exceptionally low changes of 1.00% and 0.01%, respectively—demonstrating excellent grid convergence. Although point P2 exhibits a relatively higher variation rate of 4.07%, its absolute magnitude remains small (approximately 35 Pa), implying negligible influence on the overall flow field. Furthermore, this deviation falls within the commonly accepted engineering tolerance threshold of $\leq 5\%$, confirming the adequacy of the refined mesh for accurate numerical prediction.

Table 5. Summary of Grid Independence Verification Results.

Parameters	Coarse Grid	Middle Grid	Fine Grid	Rate of Change (Medium vs. Fine)
$\Delta \bar{P}$ (Pa)	4009.26	4179.32	4217.34	0.90%
σ_p at p1 (Pa)	1910.87	1989.51	2009.70	1.00%
σ_p at p2 (Pa)	35.10	34.44	35.91	4.07%
σ_p at p3 (Pa)	344.82	332.66	332.70	0.01%
σ_p at p4 (Pa)	63.16	70.50	72.67	2.99%
σ_p at p5 (Pa)	48.68	50.68	51.80	2.16%

To provide a more intuitive assessment of grid convergence, this study presents the variation in key parameters as a function of mesh size, as illustrated in Figure 6. Figure 6a depicts the convergence behavior of the time-averaged pressure drop, a global parameter, which increases with mesh refinement but exhibits a markedly reduced rate of change (<1%) beyond the medium grid (376,949 cells), indicating asymptotic convergence. Figure 6b displays the pressure fluctuation values at two representative monitoring points, P1 and P3. Both exhibit minimal variation between the medium and fine grids—with change rates of only 1.00% and 0.01%, respectively—demonstrating insensitivity to further mesh refinement. Although point P2 shows a relatively higher change rate (4.07%), its absolute fluctuation magnitude remains small, and this deviation is isolated and does not compromise the overall conclusion of mesh convergence. Collectively, the trends in Figure 6 clearly indicate that the numerical solution has stabilized using the medium grid configuration, confirming its suitability for subsequent simulations.

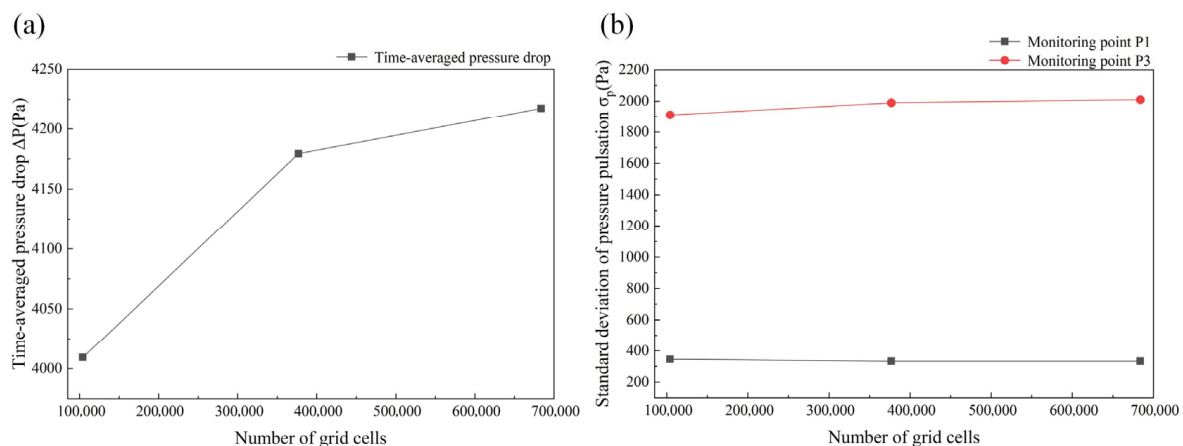


Figure 6. Grid convergence curves of key parameters. (a) Convergence curve of the global time-averaged pressure drop. (b) Convergence curve of local pressure fluctuations.

Furthermore, examination of the velocity distribution at key cross-sections of the flow field reveals consistent flow patterns across different grid configurations, further supporting the convergence behavior. The above analyses collectively indicate that increasing the mesh resolution from 376,949 to 683,905 cells yields negligible improvements in simulation accuracy. Therefore, considering the balance between computational accuracy and resource efficiency, the use of the medium grid (376,949 cells) is justified for all subsequent simulations. This configuration ensures sufficient numerical accuracy while significantly enhancing computational efficiency.

4. Results and Discussion

In this study, the influences of factors such as the drilling fluid circulation rate, rotational speed of the drill pipe, and rheological properties of the drilling fluid on the flow patterns of cuttings are investigated. On the basis of the numerical simulation results, the effects of these factors on cutting flow behavior are analyzed.

4.1. Influence of the Drilling Fluid Circulation Return Velocity on Hole Cleaning

The influences of different drilling fluid flow velocities on the cutting volume fraction at a drill pipe rotational speed of 30 rpm are shown in Figure 7. In this study, the cutting volume fraction is defined as the ratio of the volume occupied by cuttings in the entire annular space to the total volume of the annular space and represents the spatial distribution concentration of solid particles in the wellbore annulus. The view direction in the figure is along the negative y -axis, facing upward against the direction of gravity. A higher prevalence of red regions indicates a greater concentration of cuttings, whereas a predominance of blue regions corresponds to a lower concentration. Notably, as the flow velocity increases, the cutting volume fraction in the wellbore gradually decreases. At relatively low flow velocities (e.g., 0.6 m/s), the cutting volume fraction is relatively high. Under these conditions, cuttings primarily settle at the bottom of the wellbore because of gravitational forces, as the flow velocity is insufficient to effectively remove them. This inadequacy leads to the accumulation of cuttings at the bottom, adversely affecting wellbore cleanliness. As the flow velocity increases, the distribution range of cuttings gradually narrows, indicating that momentum exchange is enhanced between the drilling fluid and cuttings. This phenomenon provides an increased drag force for transporting cuttings toward the outlet, thereby improving their suspension and axial transport capacity. At increased flow velocities (e.g., 1.8 m/s), the cutting volume fraction remains nearly at its lowest level, demonstrating optimal wellbore cleaning efficiency under these conditions.

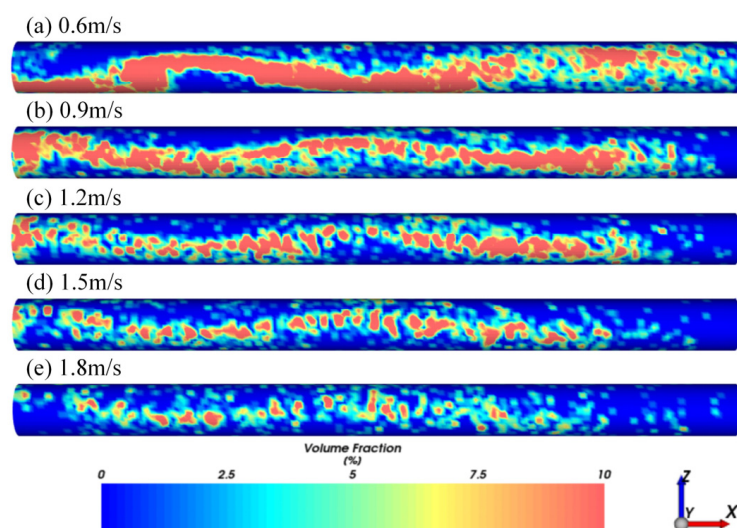


Figure 7. Contour plot of the concentration distribution of cuttings at the bottom of the annulus under different drilling fluid circulation return velocities.

The relationships between the mass of residual cuttings in the annular space and time under different drilling fluid circulation rates are shown in Figure 8. The mass of residual cuttings is defined as the total mass of cuttings remaining in the annular space between the drill pipe and the wellbore during the simulation. This parameter directly reflects the wellbore cleaning efficiency, with lower values indicating better cleaning performance. According to the data in the figure, as the drilling fluid flow rate increases, the time required

to reach the peak cutting mass decreases, and the peak value itself decreases. At higher flow rates (e.g., 1.8 m/s), the drilling fluid possesses more fluid kinetic energy and exhibits greater turbulent diffusion effects, enabling it to rapidly suspend and transport cuttings from the wellbore bottom. This phenomenon significantly enhances the wellbore cleaning efficiency per unit time, allowing the annular space to reach the critical point at which the cutting generation rate balances the removal rate quickly. Consequently, the peak occurs earlier. Additionally, owing to the increased removal capacity, the total amount of residual cuttings remaining in the annular space under these conditions is relatively low. Conversely, at relatively low flow rates (e.g., 0.6 m/s), the fluid carrying capacity is insufficient, leading to easy settlement of cuttings and the formation of a cutting bed. The removal mechanism relies primarily on bedload transport, but this process is inefficient. The annular space requires more time for cutting accumulation to achieve dynamic equilibrium, resulting in a delayed peak occurrence and a significantly higher peak cutting mass.

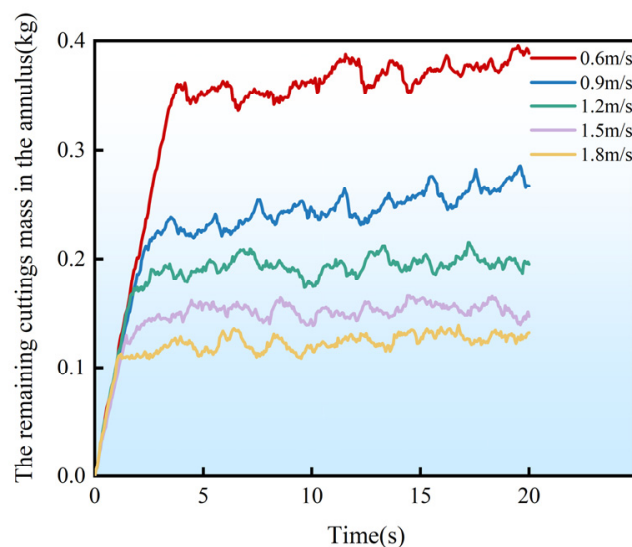


Figure 8. Variation curve of the remaining cutting mass in the annulus with time at different drilling fluid circulation return velocities.

To analyze the influence of the drilling fluid circulation rate on the cutting concentration distribution, the number of particles within the same annular section is determined, and the cutting concentration distribution curves under ten different drilling fluid circulation rates are calculated, as shown in Figure 9. Notably, as the drilling fluid flow velocity increases, the cutting concentration in the annular space gradually decreases. The most significant reduction in the cutting volume fraction occurs when the velocity increases from 0.6 m/s to 0.9 m/s, indicating that within this velocity range, improving the flow rate significantly enhances the efficiency of cutting removal. However, as the velocity further increases from 0.9 m/s to 1.2 m/s, the rate of reduction in the cutting concentration decreases, suggesting that the effectiveness of flow velocity on cutting transport begins to gradually weaken. When the velocity increases to 1.5 m/s and 1.95 m/s, the change in cutting concentration becomes almost negligible, indicating that beyond a certain flow velocity, the suspension and transport of cuttings reach a saturated state. Further increasing the flow rate provides limited improvement in cutting removal. At higher flow velocities, the incremental gain in wellbore cleaning efficiency achieved by increasing the drilling fluid flow rate is lower than that at lower velocities. Therefore, in actual drilling operations, selecting an appropriate flow velocity to achieve optimal cutting removal efficiency is necessary. Excessively high flow rates may not significantly enhance cleaning performance and can lead to increased operational costs.

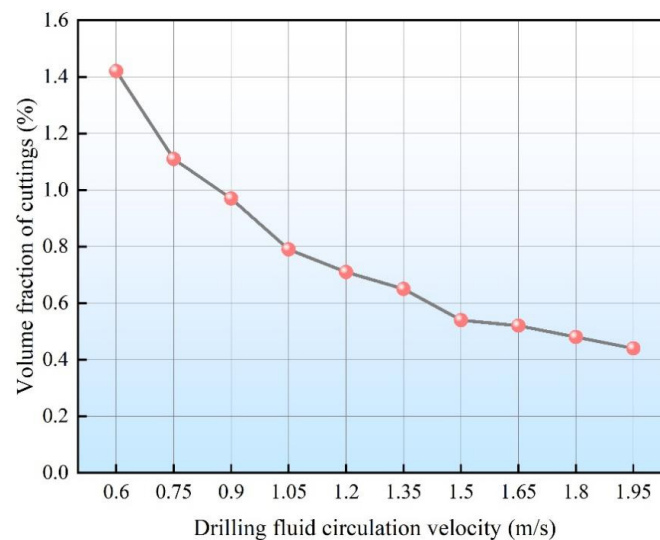


Figure 9. Concentration distribution curves of cuttings in the annulus at different drilling fluid annular return velocities.

The distributions of particle kinetic energy during cutting transport within the annular space under different drilling fluid circulation rates are shown in Figure 10a–e. The horizontal axis represents the kinetic energy associated with the translational motion of cuttings, whereas the vertical axis indicates the number of residual cuttings remaining in the annular space after the simulation reaches steady-state conditions. Notably, the kinetic energy acquired by the cuttings in the annular space increases significantly with increasing drilling fluid circulation rates. This increase in kinetic energy improves the transport capacity of cuttings, thereby progressively reducing the number of particles retained in the annular region. The primary mechanism underlying this phenomenon is that elevated drilling fluid velocities generate strengthened drag and lift forces, which effectively counteract the effects of gravity and frictional resistance on the particles. High circulation rates impart increased kinetic energy to cuttings, enabling them to effectively resist gravitational settling and adhesive forces from the wellbore wall. Consequently, the cuttings remain suspended and are continuously transported outward.

The relationship between the annular pressure drop of the flexible drill pipe and the drilling fluid flow velocity is compared in Figure 10f. As the flow velocity increases from 0.6 m/s to 1.95 m/s, the annular pressure increases from 2752.39 Pa/m to 7642.63 Pa/m, representing a 2.78-fold increase. This change is primarily attributed to the increased shear rate between the fluid and both the wellbore wall and the drill pipe at elevated velocities, resulting in increased frictional forces. Consequently, additional energy is required to maintain fluid flow, leading to an increase in the annular pressure drop. On the basis of the above analysis and this observed trend, increasing the drilling fluid velocity enhances the wellbore cleaning efficiency, as increased velocities increase the ability of the fluid to transport cuttings, accelerating their removal from the annular space. However, the accompanying significant increase in the circulatory pressure drop poses adverse effects. An increase in the pressure drop may impose additional loads on the equipment, increase the system operating pressure, and jeopardize the stability of the drilling process. Therefore, in drilling operations, merely increasing the flow velocities to improve cleaning efficiency is not advisable. Instead, finding a balance between flow velocity and circulatory pressure drop is essential to avoid the negative impacts caused by excessively high pressure drops.

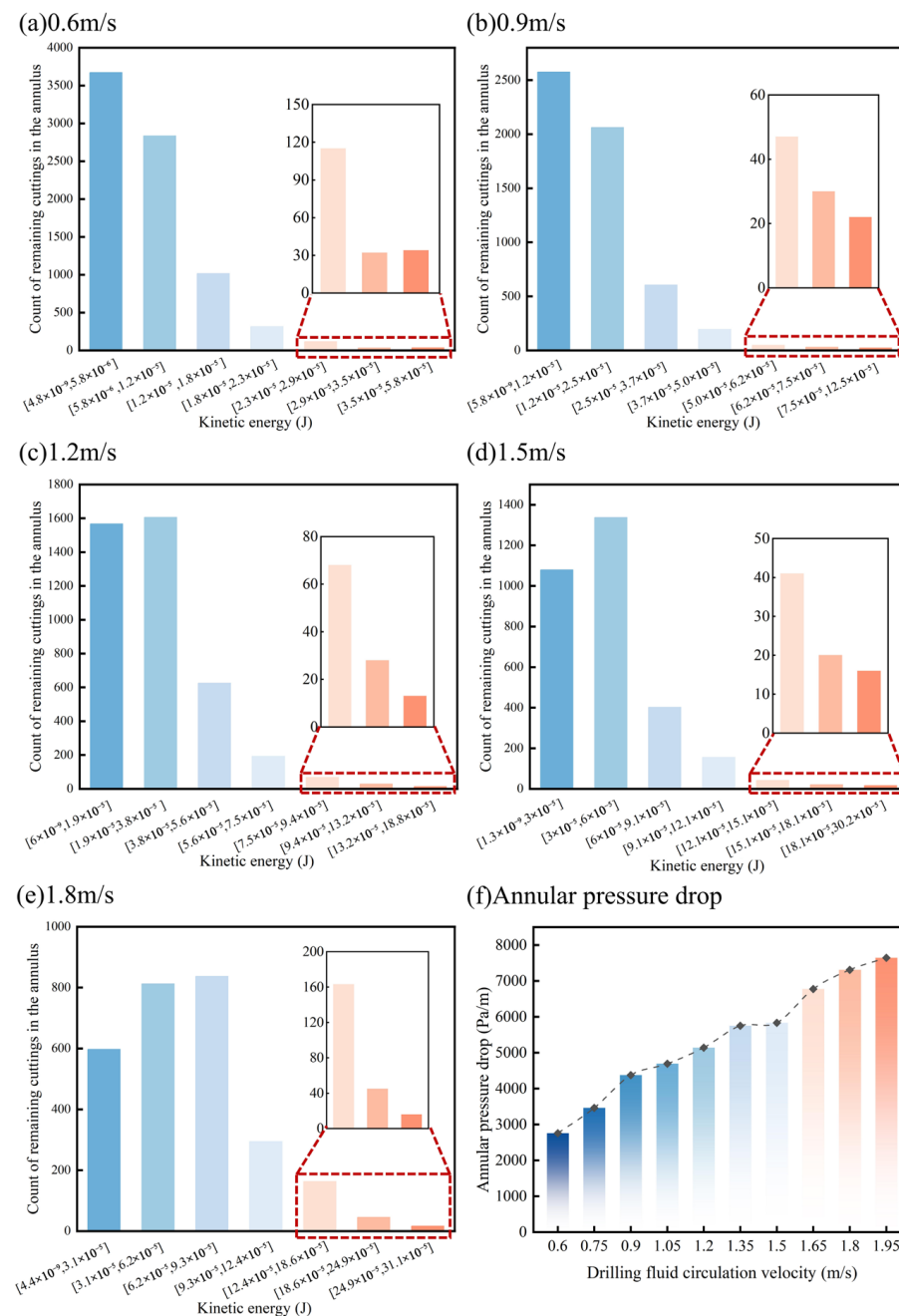


Figure 10. Kinetic energy distributions of cuttings and pressure drop variations in the annular space under different drilling fluid circulation rates.

Under different drilling fluid flow rates, the particle diameter significantly influences the transport efficiency of cuttings. In Figure 11, the horizontal axis represents the range of particle diameters, whereas the vertical axis indicates the number of residual cuttings in the annular space. A lower number of residual cuttings corresponds to a higher wellbore cleaning efficiency. Notably, as the flow rate increases from 0.6 m/s to 1.8 m/s, the number of particles across all size ranges tends to decrease, indicating improved wellbore cleaning with increasing flow rate. Further analysis reveals that the number of relatively small particles (e.g., [3, 3.2] mm) sharply decreases from 4124 to 1457 as the flow rate increases—a decrease of 64.7%. This finding suggests that smaller particles are more easily transported out of the annular space at higher flow rates. In contrast, although larger particles (e.g., [4.8, 5] mm) decrease in number as well, the level of reduction is less significant, indicating that the transport efficiency and sensitivity to changes in flow

rate are both reduced. The underlying reason for this phenomenon is as follows. For small-diameter particles, drag forces can easily overcome gravity. Even at relatively low flow rates, small particles can achieve force equilibrium or even acceleration, enabling effective suspension and transport. This phenomenon results in high sensitivity to flow rate variations. However, for large-diameter particles, gravity is dominant, and significantly increased drag forces are required to overcome it. This finding suggests that relatively high flow rates are needed to initiate and sustain their movement. In many cases, especially when flow rates are insufficient, large particles tend to roll or slide along the bottom of the annular space or accumulate in low-lying areas of the wellbore, forming depositional beds. Their transport efficiency is inherently low, making large particles far less sensitive to flow rate changes than small particles. In summary, small particles are more readily transported by fluid flow, whereas large particles require higher flow rates to initiate and maintain effective movement. Therefore, in practical drilling operations using flexible drill pipes, increasing the drilling fluid flow rate can significantly increase the cleaning efficiency for small-diameter cuttings. However, for large particles, additional technical measures must be combined to improve the wellbore cleaning efficiency.

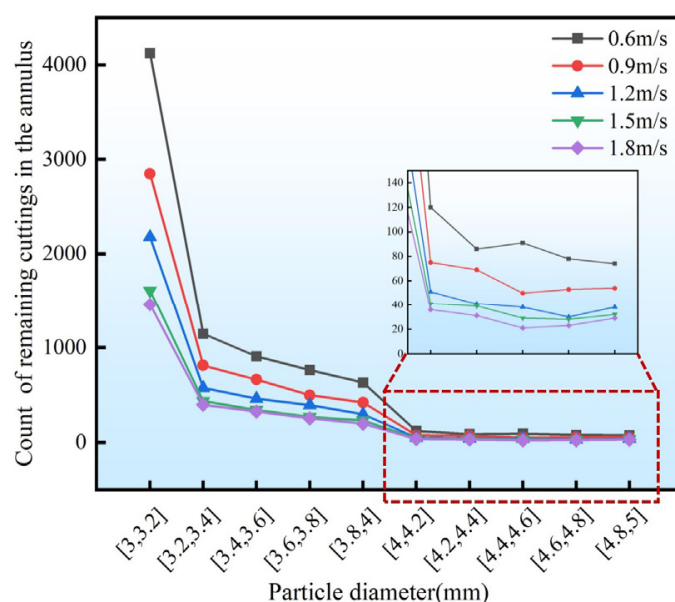


Figure 11. Variation in the number of residual cuttings in the annular space with respect to particle size under different drilling fluid circulation rates.

4.2. Influence of the Drill Pipe Rotational Speed on Wellbore Cleaning

The distribution of the cutting volume fraction in the annular section of the flexible drill pipe under different rotational speeds is shown in Figure 12. The rotation of the drill pipe significantly reduces the cutting concentration, which tends to concentrate toward the center of the wellbore. At low rotational speeds (e.g., 30 rpm), the red areas in the cloud diagram (indicating high cutting concentrations) are distributed mainly near the wellbore wall, forming a relatively distinct cutting bed. However, as the rotational speed of the drill pipe increases, the area of the cutting bed gradually decreases. This phenomenon arises due to the influence of rotational speed on the flow characteristics of the drilling fluid. At low rotational speeds, the turbulence intensity of the drilling fluid is insufficient, causing cuttings to deposit near the wellbore wall. With increasing rotational speed, enhanced turbulence and circumferential flow effects effectively agitate and suspend the cuttings, thereby facilitating their transport toward the wellhead under the action of fluid flow. Although increasing the rotational speed reduces the overall volume of cuttings, the

increase in the wellbore cleaning efficiency is smaller than that achieved by altering the drilling fluid flow rate.

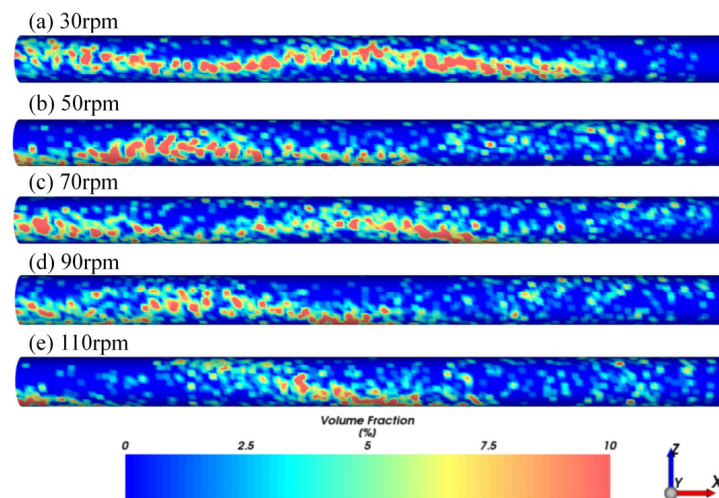


Figure 12. Distribution contours of the cutting volume fraction under different flexible drill pipe rotational speeds.

The relationships between different drill pipe rotational speeds and cutting volume fractions under a constant drilling fluid flow rate of 1.42 m/s are shown in Figure 13. The annular flow field reaches a steady state within 15 to 20 s, and data from this period are selected for analysis. As shown in Figure 13, the cutting volume fraction in the annular space clearly decreases with increasing drill pipe rotational speed. When the drill pipe rotates at 30 rpm, the cutting volume fraction is 0.58%. When the rotational speed increases to 100 rpm, the cutting volume fraction decreases to 0.51%. These results indicate that increased drill pipe rotational speeds reduce the cutting volume fraction in the annular space, thereby increasing the wellbore cleaning efficiency. The increase in cutting transport with increasing rotational speed is attributed primarily to the centrifugal force generated by rotation, which improves the ability of cuttings to detach from the drill pipe surface.

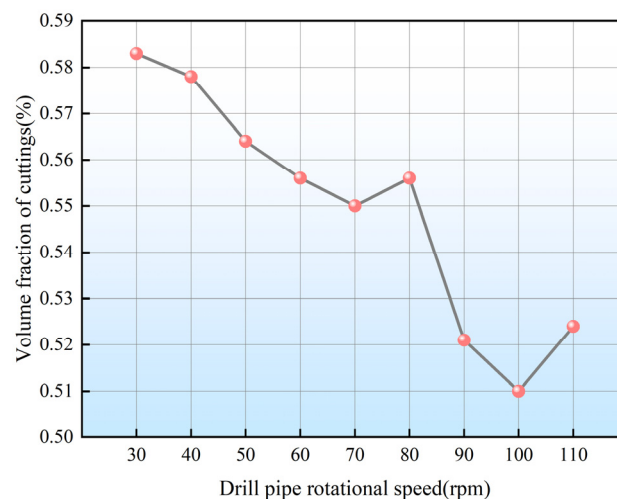


Figure 13. Distribution curves of the cutting volume fraction under different rotational speeds of the flexible drill pipe.

The distributions of particle kinetic energy during cutting transport in the annular space under different drill pipe rotational speeds are shown in Figure 14a–e. As the rotational speed of the flexible drill pipe increases, the kinetic energy of cuttings in the

annular space significantly increases, whereas the number of particles with low kinetic energies markedly decreases. These findings indicate that high drill pipe rotational speeds increase the shear force and turbulence intensity of the drilling fluid, leading to increasingly frequent collision and acceleration of cutting particles. Consequently, the motion velocity and overall kinetic energy values of the cuttings are significantly enhanced.

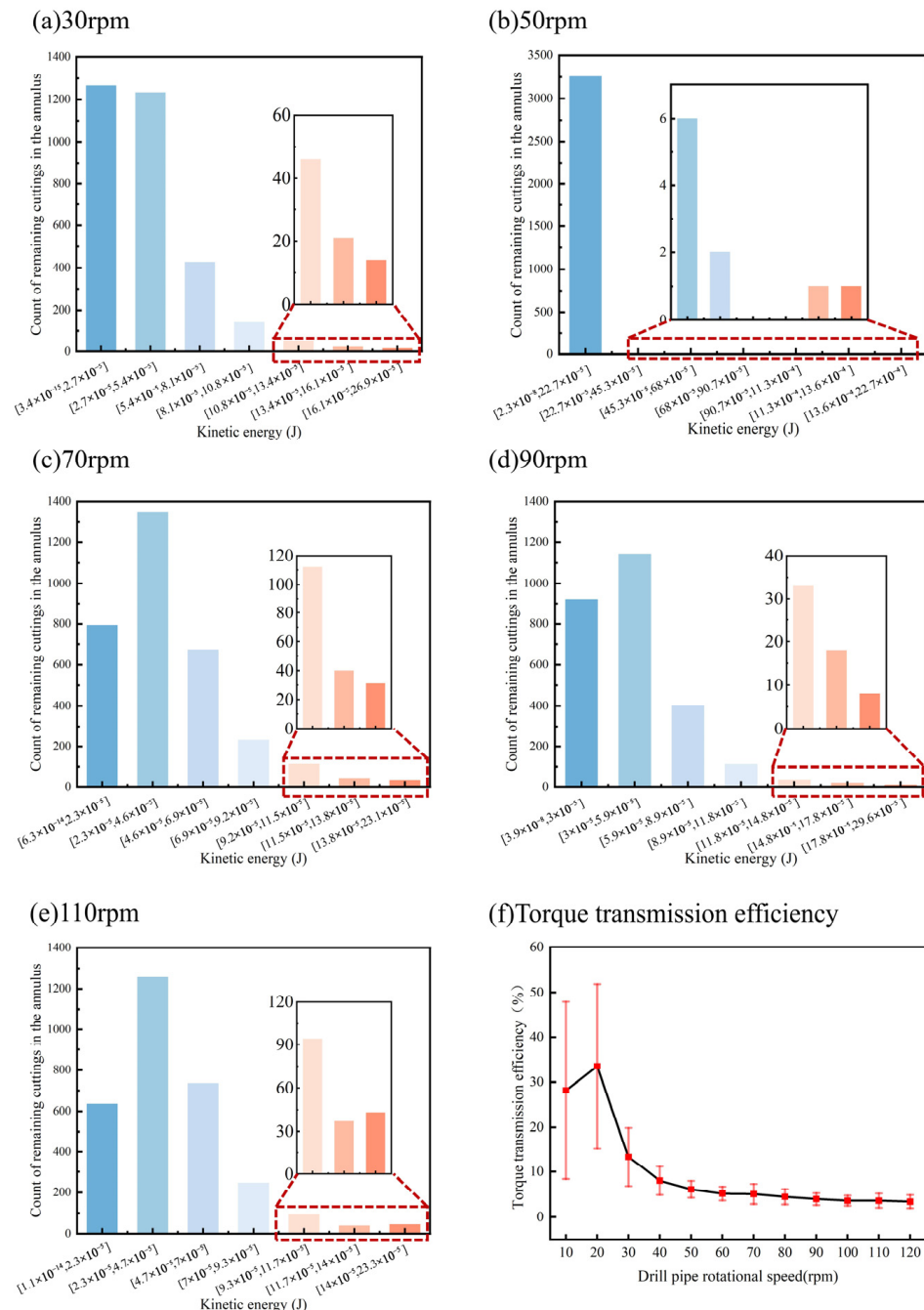


Figure 14. Variation curves of the kinetic energy distributions of cutting particles and torque transmission efficiencies in the annular region at different rotational speeds of the drill pipe.

The test results of the torque transmission efficiency of the flexible drill pipe at different rotational speeds are presented in Figure 14f. As the rotational speed increases from 30 to 110 rpm, the torque transmission efficiency significantly decreases. At 30 rpm, the torque transmission efficiency reaches 13.31% ($\pm 1.12\%$), whereas when the speed increases to 110 rpm, the efficiency sharply decreases to 3.62% ($\pm 0.84\%$), representing an efficiency loss of more than 70%. This phenomenon occurs because during high-speed rotation, the

contact frequency and intensity between the bent section of the flexible drill pipe and the wellbore wall significantly increase, leading to elevated frictional resistance. This phenomenon consumes additional input torque. Additionally, high rotational speeds may induce resonance or unstable motion of the drill pipe, further causing energy dissipation in the form of heat or other forms, thereby reducing the effective torque transmitted to the drill bit. These factors collectively contribute to the sharp decrease in torque transmission efficiency at high rotational speeds. This phenomenon indicates that while increasing the rotational speed helps increase the cutting removal efficiency in the wellbore, it simultaneously leads to a significant increase in frictional torque, substantially reducing the effective rock-breaking torque transmitted to the drill bit. Therefore, in actual drilling operations, merely pursuing high rotational speeds to optimize cutting removal is not advisable. Instead, comprehensively considering the negative impact of torque loss associated with increased rotational speed is essential. By balancing the relationship between rotational speed and torque transmission efficiency, optimal drilling parameters should be identified to achieve efficient cutting transport.

The influence of particle diameter on cutting transport behavior under different rotational speeds of the flexible drill pipe is shown in Figure 15. Analysis of the experimental data reveals that as the rotational speed increases from 30 rpm to 110 rpm, the amount of residual cuttings in the annular region does not monotonically decrease. Within most particle size ranges, the variation in particle quantity with rotational speed is relatively small, indicating that merely increasing the drill pipe rotation speed has limited effectiveness in improving borehole cleaning. Further comparison of the responses across different particle size ranges reveals that smaller particles (e.g., [3.0, 3.2] mm) exhibit relatively noticeable fluctuations in residual quantity under varying rotational speeds (e.g., decreasing to 1284 at 90 rpm but increasing to 1525 at 110 rpm), suggesting that their transport behavior is readily affected by flow field disturbances induced by drill pipe rotation. In contrast, larger particles (e.g., [4.8, 5.0] mm) show minimal changes in residual quantity, indicating that their transport behavior is less sensitive to rotational speed variations. Owing to the dominant role of gravitational settling, the rotational flow field has limited effectiveness in promoting their upward transport. This phenomenon demonstrates that while the rotation of the flexible drill pipe increases fluid disturbance in the annular region and helps prevent the settling of small particles, it does not significantly improve overall transport efficiency, particularly for larger particles. Therefore, in practical drilling operations, the rotational speed of the drill pipe must be optimized in coordination with the drilling fluid flow rate and rheological parameters to efficiently clean cuttings across the entire particle size range.

4.3. Influence of Drilling Fluid Rheological Parameters on Wellbore Cleaning

4.3.1. Effect of the Flow Behavior Index on Wellbore Cleaning

The contour plots in Figure 16 show the variations in the cutting volume fraction in the annular region under different flow behavior indices (n). For a power-law fluid with a consistency index (k) of 0.6, as n increases from 0.4 to 0.6, the residual cuttings in the wellbore gradually decrease. The primary mechanism underlying this phenomenon is that in shear-thinning fluids ($n < 1$), the apparent viscosity decreases with increasing shear rate and peaks near the wellbore wall in annular flow. Consequently, a lower n value reduces the viscosity near the wall, decreasing the ability of the fluid to suspend and transport cuttings. As n increases, the shear-thinning effect weakens, increasing the viscosity near the wall. This phenomenon enhances the cutting-carrying capacity of the fluid, thereby reducing the mass of residual cuttings. These results demonstrate that increasing the n value increases the near-wall viscosity, consequently increasing the transport efficiency of the cuttings.

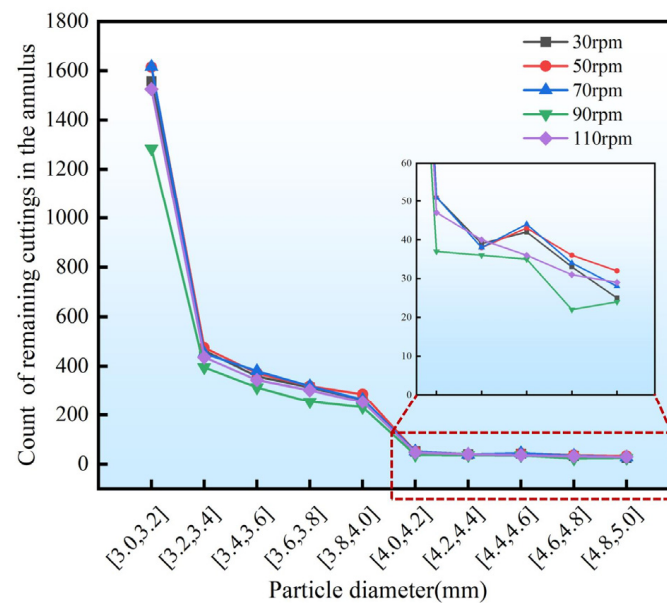


Figure 15. Variations in the number of residual cuttings in the annular region with respect to particle size at different drill pipe rotational speeds.

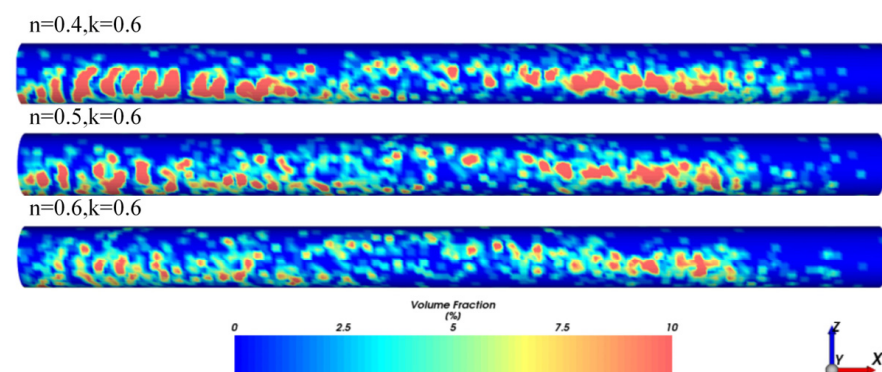


Figure 16. Cutting volume fraction in the annular region under different flow behavior indices.

The relationships between the pressure decrease and residual cutting mass in the annular region across various flow behavior indices (n) are shown in Figure 17. For a drilling fluid with a consistency index (k) of 0.6, as n increases from 0.4 to 0.6, the residual cutting mass decreases from 0.158 kg to 0.144 kg, whereas the decrease in annular pressure increases from 4293.39 Pa/m to 6456.61 Pa/m. This finding indicates that under these conditions, increasing the flow behavior index provides a limited improvement in wellbore cleaning. In shear-thinning fluids ($n < 1$), the shear-thinning behavior weakens with increasing n . During annular flow, shear stress directly governs frictional resistance at the wellbore wall, thereby determining the magnitude of the pressure drop. Consequently, as n increases from 0.4 to 0.6—although the fluid remains shear-thinning—the reduced shear-thinning intensity elevates the shear stress at identical shear rates. This phenomenon amplifies frictional resistance, progressively increasing the annular pressure drop. Therefore, indiscriminately increasing drilling fluid rheological parameters may cause excessively high annular pressure drops, potentially triggering wellbore instability. Optimization of drilling fluid properties must balance cutting removal efficiency and annular pressure control.

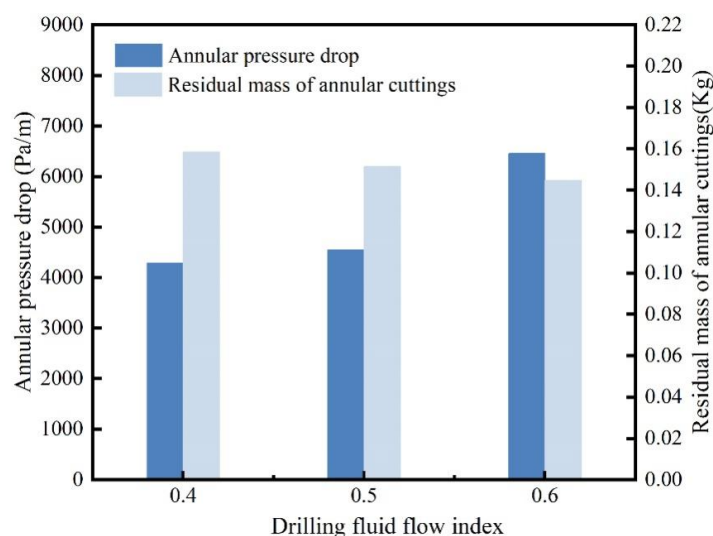


Figure 17. Pressure drop and annular residual cutting mass versus different flow behavior indices.

4.3.2. Effect of the Consistency Index on Hole Cleaning

The contour plots of the annular cutting volume fraction under different consistency indices are shown in Figure 18. For a power-law fluid with a flow behavior index of $n = 0.4$, the residual cuttings in the wellbore gradually decrease when the consistency index k increases from 0.6 to 1.5. These findings indicate that under low consistency index conditions, drilling fluids provide inadequate shear stress and structural viscosity, making it difficult to effectively overcome the gravitational settling effects of cuttings and their adhesion to the wellbore wall; this action consequently reduces the efficiency of cutting transport. With respect to relatively high consistency indices, increased viscosity enhances solid–liquid phase interactions and increases the energy of the fluid for carrying cutting particles, thereby enabling more efficient transport of cutting particles to the wellhead.

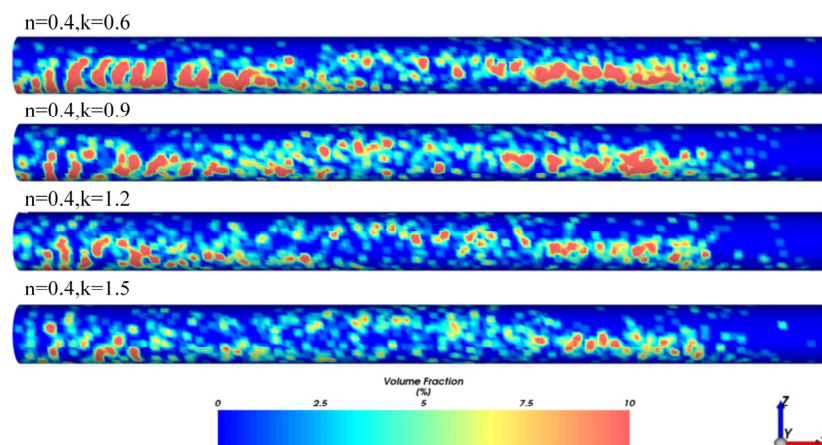


Figure 18. Annular cutting volume fractions under different consistency indices.

The relationships between the pressure drop and the remaining cutting mass in the annulus as a function of different consistency indices are shown in Figure 19. As the consistency index of the drilling fluid increases from 0.6 to 1.5, the remaining mass of the cuttings in the annulus decreases from 0.155 to 0.138 kg. With increasing consistency index, the viscosity of the drilling fluid increases, leading to an increase in apparent viscosity, which in turn increases the ability of the fluid to suspend and transport cuttings. The rheological behavior of the drilling fluid follows a power-law model, where an increase in the k value results in an increase in shear stress at the same shear rate, making the fluid

increasingly effective at preventing cuttings from settling and reducing the formation of cutting beds. Additionally, the enhanced viscosity aids in carrying cuttings out of the wellbore at high flow rates, further reducing the residual cuttings in the annulus. This trend indicates that increasing the consistency index k can optimize the cutting transport capacity of the drilling fluid and increase the hole cleaning efficiency. However, the increase in the k value is accompanied by an increase in the pressure drop, which imposes increased demands on the pump pressure. Therefore, in practical applications, considering the balance between the annular pressure drop and the cleaning efficiency is necessary.

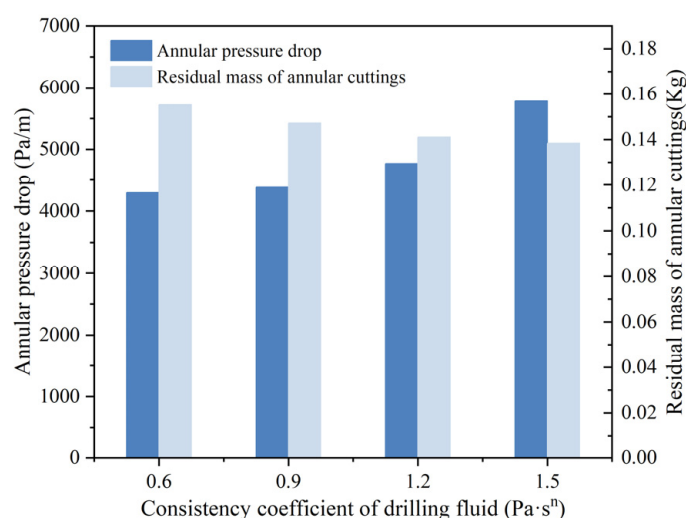


Figure 19. Pressure drop and annular residual cutting mass relative to different consistency indices.

5. Conclusions

In this study, the transport behaviors of flexible drill pipes are investigated through CFD–DEM simulations. The principal conclusions are as follows:

- (1) For flexible drill pipes rotating at 30 rpm, increasing the drilling fluid flow rate significantly reduces the annular cutting concentration and enhances the hole cleaning efficiency. The volume fraction of cuttings exhibited the most significant reduction when the flow rate increased from 0.6 m/s to 0.9 m/s. However, beyond approximately 1.5 m/s, the suspension and transport capacity of cuttings reached saturation, resulting in diminishing returns in terms of hole cleaning efficiency with further flow rate increases. Concurrently, the annular pressure drop rose sharply with increasing flow velocity, increasing from 2752.39 Pa/m at 0.6 m/s to 7642.63 Pa/m at 1.95 m/s. The improvement in hole cleaning efficiency at high flow rates is smaller compared to that observed at relatively low velocities.
- (2) At a drilling fluid flow rate of 1.42 m/s, increasing the drill pipe rotational speed of flexible drill pipes from 30 rpm to 100 rpm reduced the annular cutting volume fraction from 0.58% to 0.51%, indicating a measurable improvement in hole cleaning efficiency. However, this improvement is subject to significant limitations. First, the enhancement in wellbore cleaning efficiency achieved by increasing rotational speed is inferior to that attained through flow rate optimization. Second, higher rotational speeds primarily improve the suspension of fine cuttings (3.0–3.2 mm), but yield minimal improvement in the transport efficiency of larger cuttings (4.8–5.0 mm), which are predominantly influenced by gravitational settling. More critically, increased rotational speed results in a sharp decline in torque transmission efficiency. When the rotational speed is raised from 30 rpm to 110 rpm, torque

transmission efficiency drops from 13.31% to 3.62%, indicating that over 70% of input energy is dissipated as frictional losses.

- (3) Under power-law fluid conditions, increasing the flow behavior index n (from 0.4 to 0.6) reduces the mass of residual cuttings in the annulus from 0.158 kg to 0.144 kg, while increasing the consistency coefficient k (from 0.6 to 1.5) lowers it from 0.155 kg to 0.138 kg. These results indicate that raising either n or k enhances the cutting suspension and transport capacity. However, the improvement in cleaning efficiency is relatively limited in both cases and is accompanied by a significant increase in annular pressure drop—rising from 4293.39 Pa/m to 6456.61 Pa/m when n is increased—with a similar trend observed for k . Therefore, optimizing the rheological parameters of drilling fluid should not focus solely on increasing a single index. Instead, a comprehensive balance between cutting-carrying capacity and annular pressure loss must be achieved under specific downhole conditions to avoid excessive circulating pressure and the risk of wellbore instability.

6. Future Work

The following are the assumptions and limitations of this study and can be improved in future work.

- (1) Further simulations: Future research could focus on investigating longer flexible drill strings to further enhance the model's applicability.
- (2) Sensitivity Analysis: Due to resource limitations, the interaction force model between the fluid phase and the particle phase has not been calibrated with experimental data specific to this model. Therefore, future work could focus on calibrating the interaction forces between the particles and the fluid to improve the model's accuracy and applicability.
- (3) Validation of the Model: Due to the lack of publicly available experimental data on cutting transport in flexible drill pipes, we were unable to validate the simulation results with real-case data. Future experimental studies could address this gap.
- (4) Model extension: The model focuses solely on the horizontal section, and future work could explore methods to extend the model to include the build section.

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Conflicts of Interest: Author Qizhong Tian was employed by Sinopec Shengli Oilfield Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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