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Experimental Study on Blocky Cuttings Transport in Shale Gas Horizontal Wells

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Abstract: The widespread application of horizontal drilling technology has significantly enhanced the development efficiency of unconventional resources, particularly shale gas, by overcoming key technical challenges in reservoir exploitation. However, wellbore instability remains a critical challenge during shale gas horizontal drilling, as borehole wall collapse often results in the accumulation of large-sized cuttings (or blocky cuttings), increasing the risk of stuck pipe incidents. In this study, a large-scale circulating loop experimental system was developed to investigate the hydrodynamic behavior of blocky cuttings transport under the influence of multiple factors, including rate of penetration (ROP), well inclination, flow rate, drilling fluid rheology, and block size. The experimental results reveal that when ROP exceeds 15 m/h, the annular solid-phase concentration increases non-linearly. At a well inclination of 60°, the axial and radial components of gravitational force reach a dynamic equilibrium, resulting in the maximum cuttings bed height. To enhance cuttings transport efficiency and mitigate deposition, a minimum flow rate of 35 L/s and a drill pipe rotation speed of 90 rpm are required to maintain sufficient turbulence in the annulus. Drilling fluid plastic viscosity (PV) in the range of 65–75 mPa·s optimizes suspension efficiency while minimizing circulating pressure loss. Additionally, increasing fluid density enhances the transport efficiency of large blocky cuttings. A drill pipe rotation speed of 80 rpm is recommended to prevent the formation of sand-wave-like cuttings beds. These findings provide valuable hydrodynamic insights and practical guidelines for optimizing hole-cleaning strategies, ensuring safer and more efficient drilling operations in shale gas horizontal wells.

Keywords: shale gas horizontal wells; cuttings transport; liquid–solid two-phase flow; experimental study; hydrodynamic analysis

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1. Introduction

As the global energy landscape undergoes a profound transformation, the development of unconventional oil and gas resources has become a critical strategy for ensuring energy security [1,2]. Among these resources, shale gas reservoirs, characterized by ultra-low permeability, low porosity, and pronounced heterogeneity, pose significant challenges for efficient development [3,4]. Horizontal drilling and hydraulic fracturing have emerged as the key enabling technologies for the economic exploitation of these reservoirs. Extended-reach horizontal wells, often exceeding 1500 m in lateral length, substantially enhance well productivity by expanding the effective drainage area. However, the complexity of the wellbore architecture introduces significant engineering challenges, particularly concerning wellbore stability [5].

For deep shale reservoirs—those with burial depths exceeding 3500 m—geological and geomechanical constraints are even more pronounced [6]. These formations exhibit strong water sensitivity, high horizontal stress anisotropy, and a well-developed natural fracture network, all of which induce complex stress redistribution around the wellbore and complicate drilling operations. Field data indicate that the interaction between drilling fluids and formation fluids—primarily through filtration, adsorption, and clay hydration—can trigger shale swelling and weakening of rock strength, eventually leading to shear failure and detachment of wellbore fragments [7–9]. In the Southern Sichuan shale gas block, wellbore instability accounts for approximately 35% of non-productive time (NPT), resulting in annual economic losses exceeding CNY 1.2 billion.

The transport of large-size drill cuttings in shale gas horizontal wells is fundamentally a transient liquid–solid two-phase flow problem, involving complex momentum exchange between cuttings particles, formation fragments, and drilling fluids [10,11]. When the annular fluid velocity drops below a critical threshold, the hydrodynamic drag force becomes insufficient to counteract gravitational settling, leading to the progressive accumulation of cuttings, particularly those in the 2–10 cm size range. Previous studies have shown that the formation of cuttings beds significantly alters local flow characteristics and increases flow velocity [12,13]. This creates a dual effect: smaller particles are more easily suspended, while larger blocks tend to accumulate on the lower side of the wellbore, exhibiting intermittent movement patterns of "settling-rolling-resettling". Such behavior leads to several engineering risks, including increased contact frequency between the drill pipe and the wellbore wall, escalating contact stresses, and the risk of sticking incidents in deviated well sections due to larger cuttings [14,15]. Furthermore, the reduction in annular cross-sectional area increases equivalent circulating density (ECD), thereby raising the risks of wellbore leakage and kicks. Additionally, cuttings accumulation restricts the flow of hydraulic fracturing fluids, potentially hindering the uniform expansion of fracture networks.

Extensive research has been conducted on wellbore instability and cuttings transport in shale formations. Studies on hydration-induced stress evolution have applied models such as the Mohr–Coulomb failure criterion [16] and dual-porosity chemical–mechanical coupling models [17], revealing significant time-dependent weakening of shale formations. The effectiveness of hole cleaning is influenced by a combination of factors, including drilling fluid density, rheological properties of the drilling fluid, cuttings density, particle size, cuttings geometry, borehole dimensions, hole inclination angle, drill pipe eccentricity, drill pipe rotation speed, ROP, and drilling fluid flow rate [18–20]. However, most existing research has primarily addressed small-sized drill cuttings and steady-state flow conditions, leaving significant gaps regarding the transient transport behaviors of large-sized cuttings blocks (2–10 cm) under variable drilling parameters in horizontal wells [12,21]. This oversight limits our understanding of the dynamic interactions between cuttings bed formation and annular flow patterns, particularly under complex and varying hydraulic conditions encountered in deep shale gas drilling [22].

Efficient hole cleaning not only facilitates the effective removal of cuttings and prevents the accumulation of sediment at the bottom of the borehole but also reduces risks such as borehole blockages and stuck pipe incidents, thereby ensuring the continuity and efficiency of drilling operations [23]. The sedimentation behavior of cuttings particles plays a pivotal role in determining the cleaning efficiency. When the flow rate or rheological performance of the drilling fluid is insufficient, cuttings particles tend to settle at the bottom of the borehole due to gravitational forces, forming a stationary bed. This accumulation negatively impacts borehole stability and drilling efficiency, posing significant operational challenges.

Under ideal conditions, drilling fluids must exhibit appropriate rheological properties, such as viscosity and yield stress, to effectively suspend cuttings, particularly during

pump-off periods, preventing their sedimentation [24]. Simultaneously, maintaining sufficient annular velocity is critical to overcoming gravitational and adhesive forces, thereby transporting cuttings to the surface. The challenges associated with hole cleaning are significantly amplified in highly deviated and horizontal wells. In such wells, gravitational forces lead to increased cuttings deposition on the wellbore bottom, forming cuttings beds that impede fluid flow and reduce hole cleaning efficiency [25]. Consequently, the rheological properties of drilling fluids must be meticulously designed to achieve a balance: effectively suspending cuttings while minimizing pumping resistance. The challenges of hole cleaning are particularly acute in deep wells, ultra-deep wells, and highly deviated/horizontal wells, where wellbore instability directly affects drilling safety and efficiency [26,27]. Effective hole cleaning is essential for maintaining wellbore integrity and ensuring uninterrupted drilling progress.

In light of these challenges and the limitations of existing studies, this research specifically targets the understudied transient transport behavior of large-sized drill cuttings (2–10 cm) in inclined and horizontal sections of shale gas horizontal wells. By conducting systematic experimental investigations under varying drilling parameters and hydraulic conditions, this study aims to elucidate the detailed particle motion mechanisms and assess the effectiveness of annular hole cleaning, which have been inadequately addressed by the previous literature. Unlike prior studies predominantly focusing on steady-state conditions and small-sized particles, this work offers critical insights into the dynamic interactions between large particle cuttings, annular flow characteristics, and their impacts on wellbore stability. Ultimately, the findings will provide valuable theoretical and practical guidance for optimizing cuttings transport strategies, mitigating wellbore instability risks, and enhancing overall drilling efficiency in deep horizontal shale gas wells.

2. Experimental Setup, Materials, and Methods

2.1. Experimental Equipment

This study utilizes a large-scale closed-loop flow loop system to investigate the transportation of blocky cuttings particles in drilling fluid. As illustrated in Figure 1, the experimental setup consists of three primary components: a fluid circulation system, a data acquisition system, and a motion control system. The core test section consists of a transparent acrylic tube with a total length of 5.5 m, an outer diameter of 0.16 m, an inner diameter of 0.12 m, and a wall thickness of 20 mm. The use of acrylic ensures sufficient mechanical strength and optical transparency, enabling real-time visualization of the flow behavior of cuttings within the drilling fluid.



Figure 1. Experimental setup.

The system is equipped with a 2 m^3 stainless steel liquid storage tank (316L material) and a centrifugal pump, forming a closed-loop circulation system. The drill pipe assembly is made of precision-machined ASTM A304 stainless steel with an outer diameter of 73 mm. It is connected to a variable-speed motor (rated speed: 0–200 rpm, accuracy: ±0.5%) via a flange coupling for power transmission. Flow rate measurements are conducted using an electromagnetic flowmeter (KROHN IFM4080K, accuracy: Class 0.5), while real-time temperature compensation modules adjust fluid property parameters based on varying conditions.

2.2. Experimental Materials

The experimental materials include simulated cuttings and drilling fluid systems, as detailed below:

(1) Simulated cuttings: To mimic the behavior of blocky cuttings in the wellbore, natural gravel with a density of 1.8 g/cm^3 is mechanically crushed and sieved to achieve a particle size range of 20–40 mm (Figure 2). The particles are specifically shaped to have a flaky morphology, controlled by a two-dimensional shape factor (Feret diameter ratio) within the range of 0.25–0.35, simulating the brittle fracture characteristics of shale formations. Specifically, the blocky cuttings size in this study refers to the equivalent diameter of irregularly shaped large-size cuttings, which was determined based on a mass-to-volume conversion method. The volume of each cutting particle was estimated from its weight and known density, and the equivalent diameter was calculated assuming a spherical shape with the same volume.



Figure 2. Thin-layered gravel used for experimental simulation of blocky cuttings.

(2) Drilling fluid system: The drilling fluid used in the experiment is an oil-based mud (OBM) sample collected from an operational wellsite (Figure 3). The rheological properties of the fluid are measured using an Anton Paar Advanced Rheometer (MCR 92) to establish the flow curve. To adjust mud density, a controlled mixture of sodium chloride (NaCl) and potassium formate was introduced. The fluid was then emulsified using a high-shear emulsifier to maintain stability and ensure uniform dispersion of phase components.



Figure 3. Oil-based drilling fluid used in the experiment.

2.3. Experimental Procedure

The base drilling fluid is formulated to the target density and sequentially filtered through 100-mesh, 200-mesh, and 400-mesh screens to remove impurities. The filtered fluid is then transferred to a storage tank. A specific quantity of experimental particles is added to the fluid, and the centrifugal pump is activated while adjusting the frequency converter to achieve the target flow rate. Once the electromagnetic flowmeter stabilizes with a fluctuation of less than 1%, the system is considered stable.

After system stabilization, a sand injection system introduces drill cuttings and blocky cuttings into the fluid. The cuttings transport process is captured using high-speed imaging technology for detailed analysis.

Following the injection, the liquid–solid mixture is separated using a vibration screen, and the drilling fluid is returned to the storage tank for reuse. Once the cutting bed reaches a stable height, the position of a transparent scale is recorded to calculate the arc length of the cuttings bed. Additionally, fluid flow rates and borehole inclination angles (an inclination of 90° corresponds to a horizontal well section) are measured under different flow conditions by adjusting the frequency converter and maintaining a steady flow [28,29].

After the flow stabilizes, and the cutting bed height reaches equilibrium, the positions of three transparent markers along the exterior of the acrylic tube are recorded. These markers are used to calculate the average arc length (L) of the fixed cutting bed. The relationship between arc length and cutting bed height is illustrated in Figure 4.

The parameters in Figure 4 are calculated as follows:

$$\Omega = \frac{2L_m}{D_h + 2d_0} \tag{1}$$

$$h_1 = \frac{1}{2} D_h \cos\left(\frac{\Omega}{2}\right) \tag{2}$$

$$h = \frac{1}{2} D_h - h_1 \tag{3}$$

where: L_m is the observed arc length on the exterior of the acrylic tube; Ω is the central angle; h_1 is the height variable; d_0 is the wall thickness of the acrylic tube; D is the inner

diameter of the acrylic tube; D_h is the diameter of the borehole; D_d is the diameter of the drill pipe.

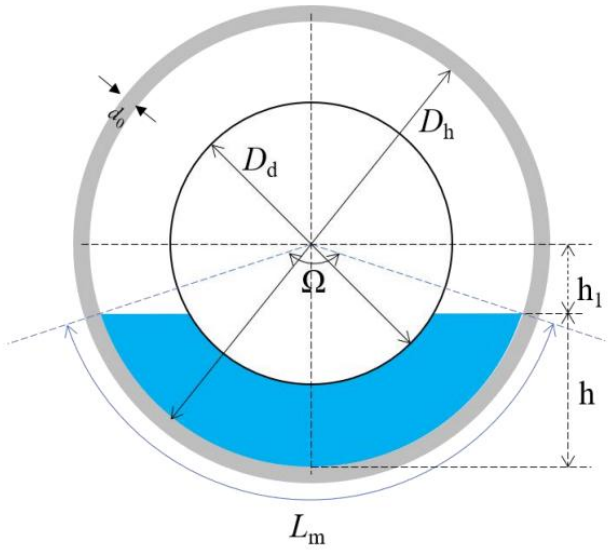


Figure 4. Relationship between arc length and cutting bed height.

During the experiment, larger block-like particles rapidly settle under the influence of gravity, forming a base cutting bed at the lower edge of the annulus, while finer particles remain suspended due to turbulent shear forces, forming a suspension layer above the base. At low flow rates, inertial effects govern particle motion, leading to a rolling-intermittent suspension transport mode. As the drill pipe rotates, centrifugal forces and secondary flows are generated, causing larger granular cuttings to be displaced from the cuttings bed toward the upper annular region. These displaced particles collide with finer cuttings, forming periodic sand wave structures [15,30]. This interaction results in transient fluctuations in flow resistance, as depicted in Figure 5.

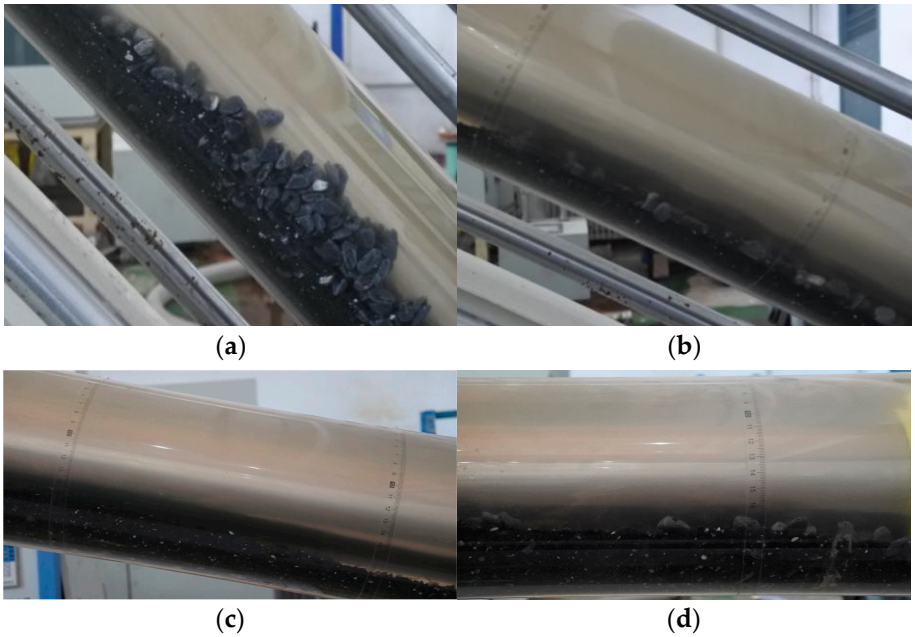


Figure 5. Schematic diagram of experimental process at: (**a**) 45° inclination; (**b**) 60° inclination; (**c**) 75° inclination; (**d**) 90° inclination.

3. Experimental Results and Analysis

3.1. Blocky Cuttings Transportation Characteristics at Different Rotational Speeds

The transportation characteristics of drill cuttings and blocks are critical in optimizing hole cleaning and reducing the risk of stuck pipe events during drilling. Understanding how rotational speed impacts the movement of cuttings with different sizes is essential for improving drilling efficiency. In this section, we explore the effects of various drilling parameters on the transportation of cuttings of different sizes under specific conditions (e.g., inclination angle of 90°, fluid properties such as plastic viscosity of 60 mPa·s, and flow rate of 30 L/s). The results of these experiments provide valuable insights into how rotational speed can influence the transport efficiency of larger and smaller cuttings particles.

As shown in Figure 6, at a ROP of 5 m/h, the experimental data indicate a strong dependence of cuttings bed height on drill pipe rotational speed. Specifically, for cuttings with diameters ranging from 20 mm to 40 mm, the bed height increased by 23–37% with a 10 mm increase in particle size (from 20 mm to 30 mm) under identical rotational speeds. The observed increase in bed height with larger blocky cuttings is attributed to several factors, with the primary mechanism being the increased critical shear stress of larger particles. As the particle size increases, their resistance to motion in the drilling fluid also increases, which leads to a reduction in the relative sliding speed of the cuttings within the fluid column. This, in turn, results in a decrease in the momentum transfer efficiency, as the larger cuttings experience more resistance when attempting to move through the fluid, leading to a slower displacement rate and a higher accumulation in the wellbore.

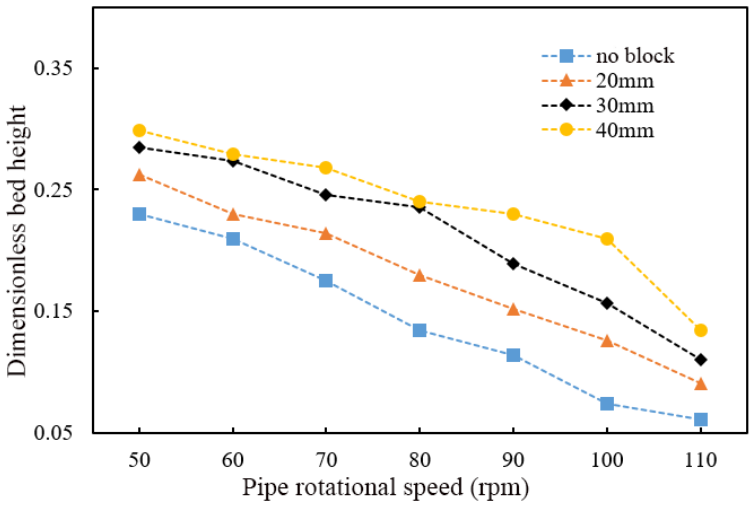


Figure 6. Variation of dimensionless cuttings bed height with rotational speed.

Furthermore, the rotational speed of the drill pipe plays a pivotal role in the efficiency of cuttings transportation. Notably, when the rotational speed was increased to the range of 90 rpm, secondary flow effects within the annulus enhanced the cuttings transport process. The centrifugal force generated by the rotating drill pipe induces a more effective circulation of the drilling fluid, leading to improved suspension and lifting of blocky cuttings. This increase in rotation speed results in a more efficient transport mechanism, particularly for larger particles in the 30–40 mm size range, which exhibited a marked increase in transport efficiency—ranging from 38% to 45%—under these enhanced rotational speeds. This increase in transport efficiency can be attributed to the fact that at higher rotational speeds, the flow patterns become more turbulent [31], leading to the creation of additional fluid shear forces that assist in overcoming the resistance posed by larger particles, thereby improving their lift and reducing the likelihood of cuttings bed formation.

3.2. Blocky Cuttings Transportation Characteristics at Different Well Inclinations

The wellbore inclination angle significantly influences the efficiency of hole cleaning and the formation of cuttings beds. At angles greater than 60°, the balance between gravitational and drag forces becomes non-linear, leading to substantial variations in cuttings transport efficiency. Figure 7 illustrates the transportation behavior of blocky cuttings ranging from 20 to 40 mm in size at different inclination angles, showing a distinct non-linear impact on the cuttings bed height. Particularly, at an inclination of 60°, a notable low efficiency in cleaning occurs, with the dimensionless cuttings bed height reaching a maximum value of 0.32 ± 0.03.

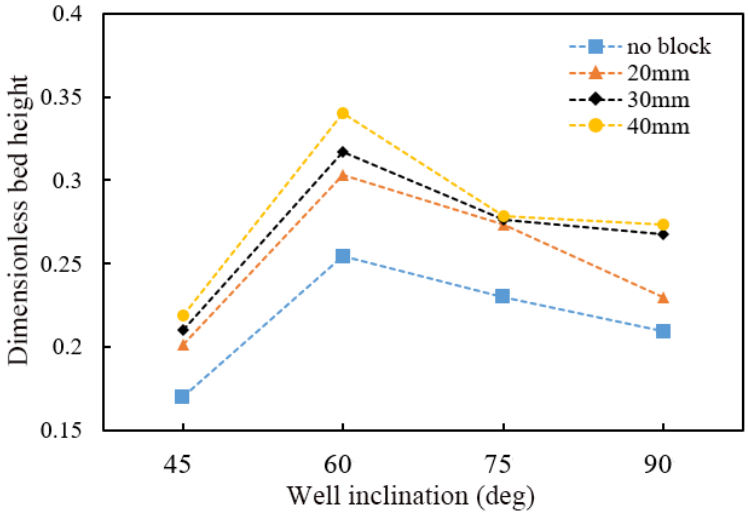


Figure 7. Variation of dimensionless cuttings bed height with wellbore inclination.

This phenomenon is explained by the dynamic equilibrium between axial and radial gravitational components at this critical angle, resulting in a quasi-static deposition at the bottom of the annular space. Notably, cuttings larger than 20 mm often exhibit a Stokes number (Stk) greater than 1, suggesting that inertia-driven motion reduces the efficiency of fluid cuttings transport. Furthermore, the data indicate significant sedimentation effects in the entry section of the wellbore, where nearly 78% of the cuttings settle within the first 1.5 m. This observation highlights the critical role of the wellbore's geometry and flow conditions in determining the behavior of drill cuttings. These findings draw attention to the limitations inherent in traditional cuttings transport models, especially in transitional flow regimes where the Reynolds number (Re) falls between 2000 and 4000. In these regimes, the flow is characterized by a combination of laminar and turbulent behaviors, resulting in insufficient turbulence to effectively suspend larger particles [32,33]. The turbulence strength is not enough to counterbalance the gravitational forces acting on the cuttings, leading to sedimentation within the wellbore. This inefficiency in cuttings transport becomes particularly pronounced when larger cuttings are involved, requiring more sophisticated models and methods for optimizing fluid dynamics in these flow conditions.

3.3. Blocky Cuttings Transportation Characteristics at Different Flow Rates

Flow rate is another critical parameter that directly impacts cuttings transport efficiency. As shown in Figure 8, variations in flow rate alter the dimensionless cuttings bed height significantly in horizontal well configuration. Increasing flow rates generally reduce the bed height, but larger cuttings, such as those with diameters between 30 and 40 mm, result in higher bed heights due to the accumulation of larger particles in the annular space. This phenomenon is explained by the critical flow rate theory, where increasing the

flow rate beyond a critical threshold creates sufficient shear stress to disrupt the structural integrity of the cuttings bed.

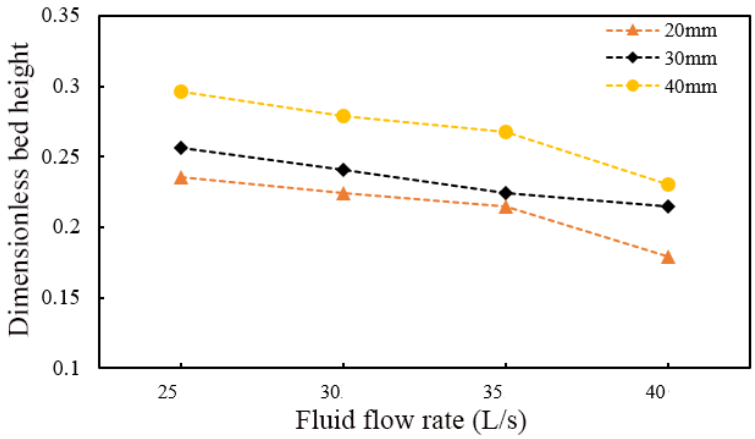


Figure 8. Variation of dimensionless cuttings bed height with flow rate.

The experimental results highlight that, when dealing with larger cuttings (≥30 mm), it is essential to adopt a synchronized strategy involving the simultaneous increase in both flow rate and rotational speed in order to enhance the efficiency of cuttings transport. This dual approach is particularly critical because large cuttings have a higher tendency to settle due to their increased size and mass, which can significantly hinder the drilling process. Based on the findings, it is recommended to adjust the flow rate to a value of 35 L/s, which has been shown to promote sufficient fluid circulation, preventing the cuttings from accumulating and facilitating their continuous transportation out of the wellbore [34]. In parallel, increasing the rotational speed of the drill pipe to a range of 80–100 rpm further assists in maintaining the suspension of the cuttings within the drilling fluid. This combination of parameters not only improves the transport of large cuttings but also minimizes the risk of cuttings bed formation, which can lead to wellbore instability and inefficiency during drilling operations. From a practical perspective, the optimization of these operational parameters, particularly for large cuttings prone to sedimentation, is crucial for maximizing drilling efficiency and reducing the likelihood of downhole issues such as stuck pipe or wellbore damage [35]. Therefore, the simultaneous adjustment of flow rate and drill pipe rotation speed should be considered a standard practice when managing large cuttings in deepwater or extended-reach well environments.

3.4. Blocky Cuttings Transportation Characteristics at Different Plastic Viscosities

The viscosity of the drilling fluid plays a crucial role in the suspension and transport of cuttings. Figure 9 illustrates how varying plastic viscosity affects the cuttings bed height. As viscosity increases, the ability of the drilling fluid to suspend and transport cuttings improves, leading to a reduction in cuttings bed height. However, when the plastic viscosity exceeds 75 mPa·s, a plateau effect is observed, where further increases in viscosity no longer yield significant improvements in wellbore cleaning efficiency.

This effect can be attributed to two fundamental fluid dynamics mechanisms. First, as the viscosity of the drilling fluid increases, the flow regime transitions from turbulent to laminar. In a turbulent flow regime, chaotic eddies and fluctuations enhance the suspension and transport of cuttings. However, as viscosity increases, the flow exhibits more orderly, layered motion characteristic of laminar flow, which significantly reduces its capacity to entrain and transport solid particles, particularly larger cuttings [36]. Second, the increase in viscosity leads to a corresponding rise in pressure loss (ΔP) along the wellbore. This elevated pressure drop results from the greater resistance to flow, which not only affects

hydraulic efficiency but may also introduce wellbore instability. Excessive pressure loss can alter the downhole pressure profile, potentially leading to unintended formation fluid influx (kick) or excessive equivalent circulating density (ECD), which could fracture the formation and induce lost circulation.

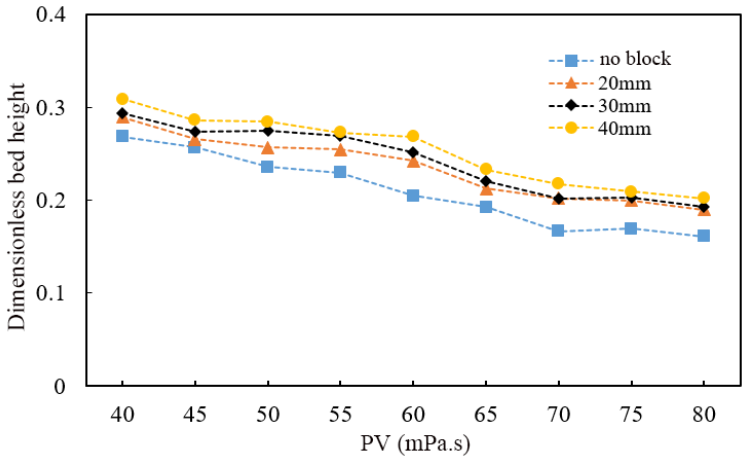


Figure 9. Variation of dimensionless cuttings bed height with plastic viscosity.

Considering these fluid dynamics effects, we recommend maintaining the plastic viscosity (PV) within the range of 65–75 mPa·s to achieve optimal cuttings transport efficiency. This viscosity range is particularly critical when managing cuttings with diameters exceeding 30 mm, as higher PV values improve the suspension capability of the drilling fluid while avoiding excessive pressure loss that could destabilize the wellbore [37–39]. Maintaining PV within this optimal range ensures an effective balance between cuttings transport efficiency and wellbore stability, which is essential for successful drilling operations in complex formations.

3.5. Blocky Cuttings Transportation Characteristics at Different Drilling Fluid Densities

Drilling fluid density is another key parameter that affects the efficiency of cuttings transport. As demonstrated in Figure 10, increasing the fluid density improves the ability to suspend cuttings and reduces the cuttings bed height. When the fluid density was increased from 1000 kg/m^3 to 1300 kg/m^3, the dimensionless cuttings bed height for both 20 mm and 40 mm particles decreased by 42.7% and 58.3%, respectively. This result can be explained by the enhanced buoyancy that reduces the effective weight of the particles, lowering their sedimentation velocity.

Interestingly, as the density of the drilling fluid increases, the influence of particle size on cuttings transport efficiency becomes significantly less pronounced. Specifically, when the fluid density exceeds 1.2 g/cm^3, the difference in settling height between 20 mm and 40 mm particles decreases markedly. This observation suggests that an increase in fluid density enhances the buoyant forces acting on the cuttings, thereby reducing the disparity in sedimentation behavior across different particle sizes. From a practical engineering perspective, increasing the density of drilling fluids is a widely employed strategy to improve the transport efficiency of large cuttings in wellbores, particularly in deepwater and deep-strata drilling operations where cuttings removal is challenging [40]. The enhanced buoyancy and viscous drag provided by higher-density fluids facilitate the suspension and upward transport of large particles, preventing their premature settling and potential accumulation at the bottom of the wellbore. This is especially critical in extended-reach wells (ERWs) and horizontal drilling, where inadequate cuttings transport can lead to the formation of cuttings beds, causing increased torque, drag, and even wellbore blockage.

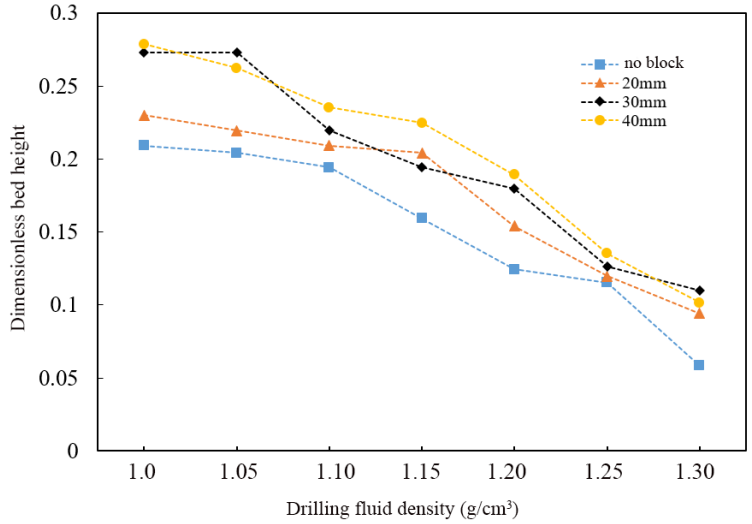


Figure 10. Variation of dimensionless cuttings bed height with drilling fluid density.

However, despite its benefits in cuttings suspension, increasing fluid density also introduces a series of operational challenges that must be carefully managed. A higher-density fluid leads to an elevation in hydraulic pressure, which, if not properly controlled, may exacerbate wellbore instability, particularly in formations with low fracture gradients. Excessive downhole pressure can induce formation breakdown or lost circulation, jeopardizing well integrity and increasing non-productive time (NPT). Moreover, higher-density fluids tend to exhibit greater viscosity, which can increase pump energy requirements and reduce overall drilling efficiency. Therefore, optimizing fluid density requires a delicate balance between cuttings transport efficiency and the associated risks of excessive hydraulic pressure and wellbore instability.

3.6. Blocky Cuttings Transportation Characteristics at Different Cuttings Sizes

The size of cuttings plays a critical role in their transportation and deposition within the annular space. As shown in Figure 11, increasing the particle size from 20 mm to 40 mm results in a significant increase in cuttings bed height, with the maximum increase reaching 37.6%. Larger particles, due to their higher inertia, tend to settle faster than smaller particles, which poses challenges for effective cuttings transport.

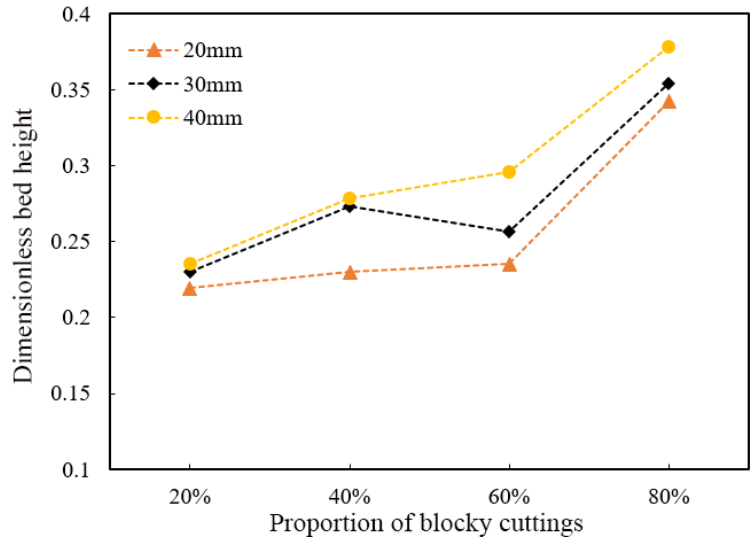


Figure 11. Variation of dimensionless cuttings bed height with blocky cuttings size.

When the block content exceeds 60%, the bed structure becomes unstable, forming non-uniform sand waves, leading to increased local flow resistance and potentially causing "severe stuck pipe" events. The results indicate that for blocky cuttings with a content of 40% or more, rotational speed should be increased to at least 80 rpm to enhance the centrifugal effect and break the mechanical balance of particle deposition, thereby improving wellbore cleaning efficiency. When the volumetric concentration of blocks exceeds 60%, the structural stability of the cuttings bed deteriorates significantly. This instability manifests as the formation of non-uniform sand waves, characterized by irregular particle deposition patterns and localized agglomeration. These irregularities contribute to substantial variation in local flow resistance, which can disrupt the overall drilling fluid circulation and exacerbate the risk of differential pressure sticking [29]. In extreme cases, this phenomenon may lead to "severe stuck pipe" incidents, posing significant operational hazards and complicating wellbore recovery efforts.

Experimental results further demonstrate that when the block concentration exceeds 40%, maintaining effective hole cleaning requires an increase in rotational speed to at least 80 rpm. This enhanced rotation induces a stronger centrifugal force, effectively disrupting the mechanical equilibrium governing cuttings deposition. By intensifying the tangential and radial forces acting on the cuttings, the increased rotational speed reduces the tendency of particles to settle and accumulate along the lower wellbore annulus. Consequently, this strategy optimizes cuttings transport efficiency, reduces the likelihood of cuttings bed formation, and enhances overall wellbore stability.

3.7. Blocky Cuttings Transportation Characteristics at Different ROPs

The rate of penetration (ROP) has a substantial impact on the transport efficiency of cuttings. ROP is defined as the axial drilling speed (typically in m/h), and the corresponding cuttings generation rate was calculated based on the total borehole volume removed per unit time and the bulk density of the formation. As illustrated in Figure 12, at ROP values below 5 m/h, the balance between cuttings generation and the ability of the drilling fluid to transport the blocky cuttings is maintained, resulting in a stable cuttings bed. However, as ROP increases, the generation of cuttings outpaces the fluid's ability to transport them, leading to thicker cuttings beds in the annular space. This is particularly problematic when the particle sizes are concentrated in the 30–40 mm range, where layering phenomena are observed due to the differential settling of larger and smaller particles.

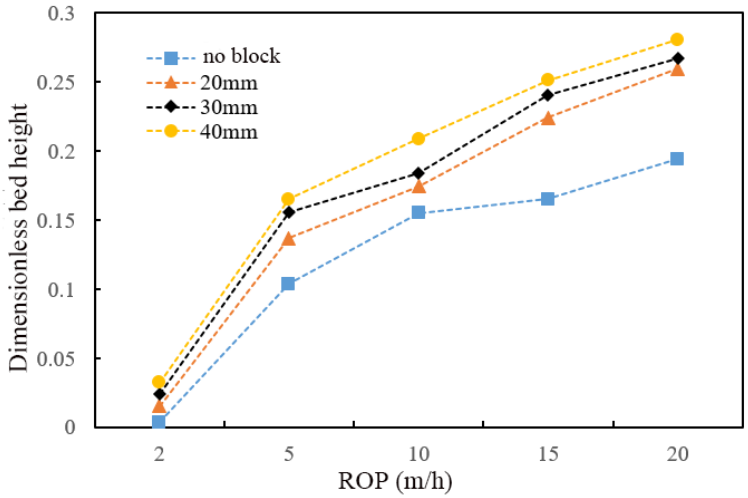


Figure 12. Variation of dimensionless cuttings bed height with ROP.

As the ROP exceeds 15 m/h, the transport capacity of the drilling fluid is significantly challenged. High ROPs result in the generation of a large volume of cuttings, which may not be effectively removed by the circulating drilling fluid, leading to the formation of a substantial cuttings bed within the wellbore. This accumulation of cuttings increases the risk of stuck pipe events, as the cuttings can obstruct the flow of drilling fluid, leading to increased friction between the drill string and the wellbore. Such blockages not only reduce the cleaning efficiency of the wellbore but also exacerbate the likelihood of stuck pipe occurrences, where the drill string becomes physically bound within the wellbore due to excessive cuttings or debris accumulation. To optimize ROP, a multi-objective approach is required. This approach must balance drilling efficiency with factors such as cuttings bed height, equivalent circulating density (ECD), and wellbore cleaning performance. While increasing the ROP enhances drilling efficiency, it simultaneously increases the volume of cuttings generated, necessitating the enhancement of the drilling fluid's ability to transport and suspend these cuttings [41]. Moreover, as ROP increases, the ECD also tends to rise, which can increase wellbore pressure and exacerbate the risk of stuck pipe if the pressure exceeds the fracture gradient of the formation or the pressure limitations of the equipment.

An effective optimization strategy for ROP involves dynamically adjusting drilling parameters, including drilling fluid properties and pump rates, based on real-time monitoring of wellbore conditions. This includes maintaining the cuttings bed height within a manageable range and ensuring that the ECD remains below critical thresholds that could risk wellbore integrity. Additionally, it is crucial to consider the geological characteristics of the formation, such as pore pressure, rock strength, and the angle of inclination of the well, to adapt the drilling process for each unique environment. By achieving this balance, the drilling process can be made safer, more efficient, and cost-effective, while minimizing the risk of stuck pipe incidents.

It is worth noting that this study primarily focuses on the influence of individual drilling parameters under controlled laboratory conditions. While this approach enables the isolation and quantification of key factors affecting blocky cuttings transport, it does not fully capture the complex interactive effects that may occur in field environments. Therefore, future research will aim to incorporate multi-factor experimental designs and real-time monitoring technologies, in order to more comprehensively characterize the coupled dynamics of cuttings transport in actual drilling operations. This planned continuation will help bridge the remaining gaps and validate the experimental insights under more realistic and operationally relevant conditions.

The transport behavior of large blocky cuttings under transient flow conditions is governed by complex and highly nonlinear interactions among multiple influencing parameters. Developing a unified empirical correlation that captures these interactions would require extensive parametric coverage and a comprehensive full-factorial experimental design, which is beyond the scope of the present study. Therefore, the current work focuses on qualitatively analyzing the influence trends of key factors and identifying critical threshold conditions for efficient cuttings transport. Nevertheless, the potential value of such integrated correlations is fully acknowledged, and future research will aim to explore this direction by employing data-driven modeling approaches—such as machine learning techniques—based on an expanded experimental dataset, with model performance evaluated using advanced statistical metrics such as the average normalized mean-squared error (ANMSE), relative error (RE), and root mean squared logarithmic error (RMSLE) [42,43].

4. Conclusions

This study systematically quantifies the influence of key parameters on the transportation behavior of shale gas horizontal well borehole instability and its impact on hole cleaning efficiency. Key parameters, including drilling fluid rheology, flow rate, well inclination, cuttings size distribution, and the interaction between cuttings and drilling fluid, are examined to establish their respective roles in cuttings transport efficiency. Based on these findings, it proposes control strategies, providing technical guidance for maintaining borehole stability and efficient cuttings transport in shale gas horizontal wells. The main conclusions drawn from the research are as follows:

When the ROP is less than 5 m/h, a dynamic equilibrium is established between cuttings generation and transportation capacity, with the cuttings bed remaining stable at or below 0.15 m. However, when ROP exceeds 15 m/h, the solid-phase concentration surpasses the critical threshold of 18.6%, leading to a sharp increase in cuttings bed height, indicating a strong negative influence on transport performance. It is recommended to dynamically adjust the ROP and flow rate to balance drilling efficiency and cuttings transport challenges.

A 60° inclination angle is identified as a critical point of low hole cleaning efficiency, with the cuttings bed height reaching 0.32 ± 0.03 m, representing the most unfavorable inclination for hole cleaning. To mitigate this, prolonged operations at this angle should be avoided. Instead, increasing the flow rate to 35 L/s combined with a drill pipe rotation speed of 90 rpm should be employed to use centrifugal forces to disrupt particle deposition and improve cleaning efficiency.

At a flow rate of 30 L/s, a 40 mm cuttings size leads to a 58.7% increase in cuttings bed height compared to a 20 mm cuttings size scenario, making particle size one of the most sensitive parameters. For cuttings larger than 30 mm, it is recommended to implement a collaborative strategy using a flow rate of 35 L/s and a drill pipe rotation speed of 80–100 rpm, which can reduce cuttings bed height by 42%.

A plastic viscosity of 65–75 mPa·s is effective for suspending larger cuttings, resulting in a 40% reduction in cuttings bed height, showing its critical role in suspension stability. When the density is increased to 1200 kg/m^3, the Reynolds number for 40 mm cuttings drops below 100, significantly enhancing suspension stability.

When the equivalent diameter of cuttings increases to 40 mm, the cuttings bed height increases by 37.6%. If the cuttings volume exceeds 40%, it is essential to increase the drill pipe rotation speed ($\geq$80 rpm) to suppress transient pressure fluctuations caused by sand wave-like cuttings beds.

Compared with previous studies focusing mainly on smaller particle sizes (typically <10 mm) and steady-state flow conditions, the present work addresses a critical gap by investigating the transient transport behavior of larger cuttings blocks (20–40 mm) under variable operational parameters. The quantitative findings—such as the critical thresholds for ROP, flow rate, and plastic viscosity—complement and extend cuttings transport behavior by incorporating more realistic field-scale cuttings geometries and dynamic flow characteristics. This contribution offers practical insights for improving hole cleaning strategies and enhancing operational safety in deep horizontal shale gas wells.

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