Cuttings Removal in Eccentric Geometries: A Comprehensive Review of Hole Cleaning Mechanism, Affecting Parameters, and Assessment

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Abstract

Horizontal and deviated wells offer higher drainage areas through reservoirs than vertical wells do. Such drilling techniques are globally employed to keep up with the growing demand for energy and provide extra fuel resources. However, inadequate hole cleaning (HC) has grown to be a challenge that may pose technical issues such as lower rate of penetration, excessive torque and drag or even stuck pipe. Furthermore, deviated annulus might be typically eccentric because of the weight of the drill string accompanied by intense drilling oscillations during directional drilling. Hence, this makes the task of HC more challenging. Numerous HC models and down hole technologies are employed for better cutting transport from down deviated and horizontal wellbores up to the surface. This paper investigates most of innovative equipment and down hole assemblies used in deviated and horizontal wells as well as the mechanism of cutting transport through each wellbore trajectory. Additionally, it provides a comprehensive review of the most influencing aspects including rheological, geometrical, drilling operational parameters, cuttings characteristics and sweeps. Modeling and geometrical definition of eccentric annulus are assessed and graphically evaluated. Further, the potential of experimental, intelligent, computational fluid dynamics (CFD) real time applications is addressed, and their recent achievements are discussed. Finally, general conclusions and further recommendations are suggested to overcome HC issues, aid in assemblies/drilling fluid selection, and optimize the whole drilling operation for more efficient HC in directional and eccentric wells.

Introduction

To keep up with the growing demand for energy, directional well drilling techniques are widely employed. These techniques might effectively improve single-well productivity as well as the contact drainage area of oil and gas reservoirs. According to drilling records, a horizontal well may produce up to three to eight times as much as a vertical well cumulatively, but its cost will be around 1.2-2 times higher (Yan et al. 2020).

Wellbore stability and cutting removal are among the biggest challenges in deviated and horizontal wells (Mitchell 2007). Poor hole cleaning (HC), which mostly affects the deviated and horizontal sections of oil and gas wells, is the most frequent issue that arises in complicated well trajectories (Sun et al. 2013). This issue is

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attributed to the accumulation of cuttings that may lead to a reduction in the rate of penetration (ROP) in both horizontal and inclined wells, as well as an increase in friction and torque on the eccentric drill string. Further poor HC can cause problems, such as hole pack-off or stuck pipe (Qu et al. 2021; Yeo et al. 2021; Saad et al. 2024). Furthermore, cutting accumulation was found to be avoidable for strongly inclined drill sections when the inner and outer pipes were co-centered (concentric), and vice versa (Tomren et al. 1986; Yu et al. 2007). Cuttings build up results in excessive torque on the drill string that increases wear forces due to the added friction on drilling equipment and bottom hole assemblies (Busch and Johansen 2020; Khosravanian and Aadnøy 2021; Al-Shargabi et al. 2024).

There are various significant parameters that affect cuttings removal mechanism in directional wells including: wellbore geometries, drilling fluid rheology, cuttings properties, drilling operation parameters, and mud properties (Khaled et al. 2021; Zhu et al. 2021). Additionally, HC indicators such as pipe hole eccentricity, carrying capacity index (CCI), cutting concentration (CA), cutting slip velocity, and transport velocity (V_T) may have direct impact on the HC process especially in deviated wells (Mohammadzadeh et al. 2016; Rehman et al. 2019; Erge and van Oort 2020; Busch et al. 2020; Saad et al. 2024). However, it is still challenging to assign defined values to their relative importance and interdependency on the wellbore cleanout process (Heydari et al. 2017). Results revealed by Saad et al. (2024) indicated that, transport ratio, CCI and equivalent circulating density (ECD) had the highest relative significance on CA, especially in eccentric annuli while deviated well drilling up to 62º of inclination. Cutting transport in horizontal and inclined wellbores is negatively affected drill pipe eccentricity (Walker and Li, 2000). Cuttings can be transported by the flow stream if proper annular fluid velocity and viscosity are maintained. In such conditions, HC process can be reasonably managed as the cuttings settle in the opposite flow direction (Sun et al. 2023).

A well is considered extended reach (ER) if its horizontal displacement exceeds 20,000 ft or if the ratio of its horizontal reach (departure) to true vertical depth (TVD) is more than 2. In essence, directional drilling or horizontal drilling technology has evolved to become extended reach drilling (ERD) technology (El Sabeh et al. 2023). Directional and horizontal drilling methods are both used in ERD. Although ER well is a far better option for increasing the contact length of wellbore with the reservoir and/or multiple separate reservoirs, its implementation can lead to issues including HC, increased torque and drag, and higher ECD. Unfortunately, these challenges only get harder to solve as wellbore length increases (Hemphill and Tom 1997).

Horizontal wells may have greater bottom hole circulation temperatures than vertical wells. In high-pressure and high-temperature (HPHT) applications, that risk might be considerably higher, where static geothermal temperatures can exceed 320°–350°F. The horizontal wellbore profile and HPHT conditions together provide a formidable obstacle to accomplishing the main goals of drilling. Moreover, denser cuttings settle more quickly than less dense cuttings, which makes it harder to clean out from the wellbore. Further, drill pipe rotational speed has a significant impact on HC efficiency as well. Further, high drilling fluid density is employed to regulate pressure under HPHT conditions, which speeds up the settling of solid barite particle of drilling fluids. Drilling parameters and fluid qualities have an impact on this settling, which might result in stuck pipes, unstable wellbores, loss of circulation, and abnormal rheo-logical characteristics (Al-Rubaii et al. 2023).

For years, the problem of HC has been thoroughly investigated. Despite the recent significant advancements, it is still a major challenge, especially in deviated and horizontal wells. Additionally, HC and its influencing parameters have been the subjects of extensive researches that have adopted developed numerical models (Pereira et al. 2007; Yilmaz, 2012; Demiralp, 2014; Wang et al. 2021; Yeo et al. 2021), and experimental studies using flow-loop apparatus that replicates the drill string and annulus of a borehole and circulates test fluids and cuttings (Leporini et al. 2019; Chowdhury and Hovda, 2022; Pedrosa et al. 2022, 2023; Skenderija et al. 2023). Experimental studies have been the direct and the most accurate method for evaluating CA as an HC efficiency indicator in the wellbore. However, the experimental models have a limitation of conducting cuttings transport experiments under downhole conditions (Ford et al.1990; Heshamudin et al. 2019; Oseh et al. 2020).

This work outlines the difficulties posed by HC and suggests methods for optimizing drilling operational parameters and assessing useful drilling assemblies/equipment for a successful drilling operation especially in deviated and eccentric wellbores. Particularly, the direct HC indicators such as: CCI, CA, V_T in addition to the drilling fluid (properties, rheology, and sweeps), wellbore inclination/geometry, and drilled cuttings (shape, size, and density) are thoroughly discussed. Further, this review discusses and evaluates the published HC research either experimental work, numerical simulation or intelligent models. Relying on the results of prior reviews (Mahmoud et al. 2020; Al-Shargabi et al. 2024), this review is scoped and presented to give readers a thorough grasp of contemporary methods, HC problems identification and improvements. Additionally, it highlights the HC issues that are most likely to occur in the context of directional and horizontal well profiles as well as the most potential areas for additional research and development that may lead to even better HC performance. In summary, this comprehensive review broadens the scope of the concerns covered by earlier HC studies through addressing the following objectives:

- Review the cutting transport mechanisms in directional wellbore geometries as well as the effect of bottom hole assembly (BHA) and drill string configuration on HC.
- Assess and identify various geometrical and drilling fluid rheological parameters that affect HC in deviated and horizontal wells.
- Discuss and evaluate drilling parameters and equipment required for adequate HC efficiency in horizontal and deviated wellbores.
- Discuss the experimental, numerical, and intelligent models implemented to analyze cutting removal and estimate CA in deviated and horizontal annuli and raise the novelties.
- Provide a geometrical definition of eccentric annulus and review previous HC models in eccentric wells.
- Provide recommendations for future HC research and methods to improve drilling efficiency.

The sequence of steps taken to achieve the objectives of this review work are as follows: The paper firstly gives an explanation of cutting transport in deviated and horizontal wellbores. Secondly, the influence of different parameters on HC in deviated and horizontal wells is discussed. Followed, a noteworthy geometrical definition and modeling studies of the eccentric annulus are summarized and reviewed. After that, a discussion is conducted on the HC efficiency assessment using artificial Intelligence (AI)/machine Learning (ML), CFD simulation, and experimental modeling. Finally, conclusions and recommendations are drawn to present guidelines for field applications and for further research in HC while directional drilling operations. **Figure 1** depicts a schematic illustration of the work scheme of HC review in this paper.

Cutting Transport in Deviated and Horizontal Wellbores

In the following section the mechanism of drill cuttings transport in horizontal and deviated wellbore profiles, the principal forces acting on drill cuttings, and the transport mechanism in the annulus for various angles of inclination and flow velocities have been summarized and discussed. Further, this section discusses the essential drilling equipment, accessories, and BHA required for efficient HC conditions.

Mechanism of Drill Cuttings Transport in Horizontal and Deviated Wellbores. In addition to the difficulties experienced in drilling vertical, directional wells may provide extra set of challenges (Zhu et al. 2013). Pang et al. (2023) illustrated the mechanism of cutting transport in horizontal wells. As seen in **Figure 2**, drill bit jets the drilling fluid which is injected into the drill pipe from the wellhead to the bottom hole. Then, the drilling fluid returns cuttings up to the surface through the annulus. However, cutting beds are formed when cutting particles are settled downhole the horizontal and deviated well sections.

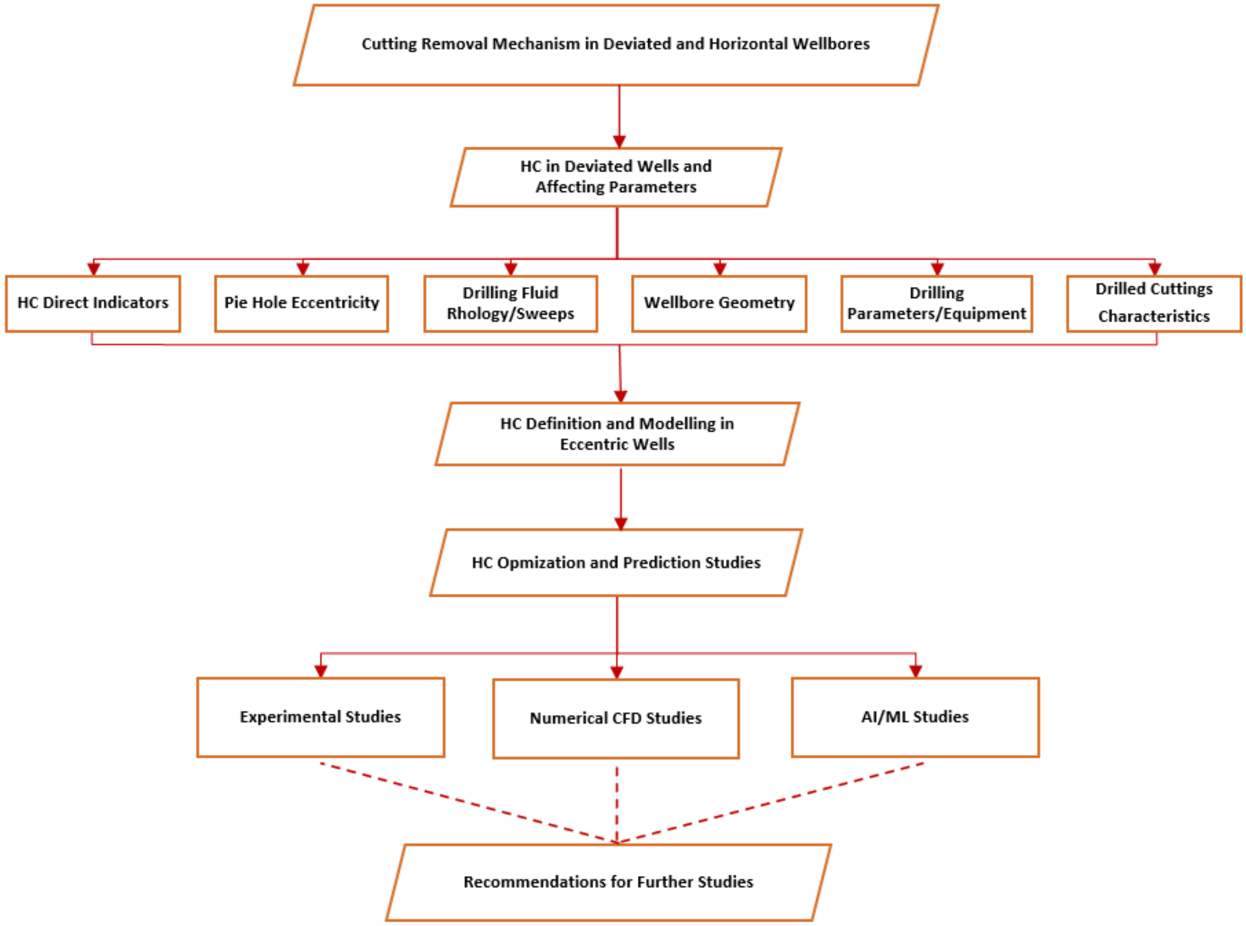


Figure 1—Schematic illustration of the work scheme of this review.

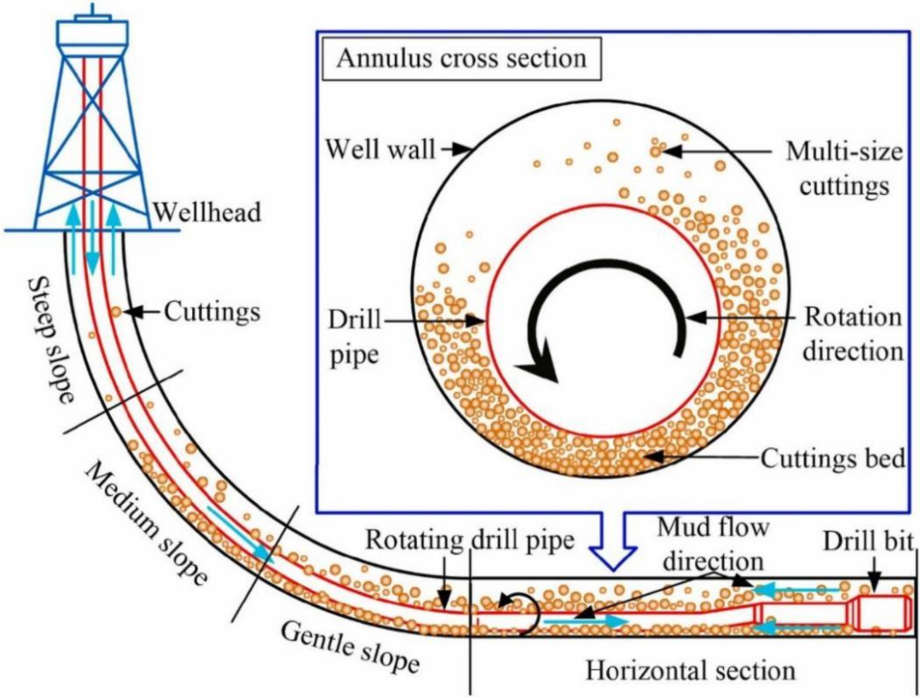


Figure 2—Schematic illustration of cutting transport mechanism in horizontal well (Pang et al. 2023).

Following, the formed compacted cuttings bed may cause serious drilling issues, such as early bit wear, excessive torque and drag, or even pipe sticking. This will add a degree of difficulty in drilling a well which is usually reflected in the time taken to complete the well and the total drilling cost. As depicted from **Figure 3**, the extra time and the overall cost of drilling needed to sidetrack a well as a remedial solution due to encountered problems, typically indicate the degree of difficulty involved in directional drilling operations (Inglis 1987).

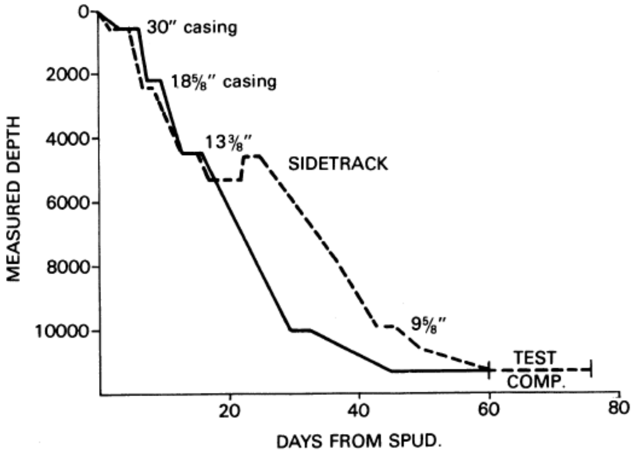


Figure 3—Depth vs time graph demonstrating effect of sidetracking while directional drilling (Inglis 1987).

Figure 4 shows a basic schematic of the movement of the dunes in the horizontal section of the borehole. It demonstrates how the rolling mechanism moves solid cuttings from the sand dunes' outer layer at a slow drilling fluid velocity (Huque et al. 2021). According to Mahmoud et al. (2020), a particle suspended in a fluid stream is subjected to four different forces: drag, lift, gravity and buoyancy forces. **Figure 5** depicts these principal forces acting on drill cuttings that influence the HC process. The drag and lift forces act on cutting particles. Drag force is determined by the particle projection area, drag coefficient, and relative velocity between the particle and the surrounding fluid. Gravity force is proportional to particle mass and gravitational acceleration. The buoyancy force is affected by fluid density, particle size, and gravitational acceleration.

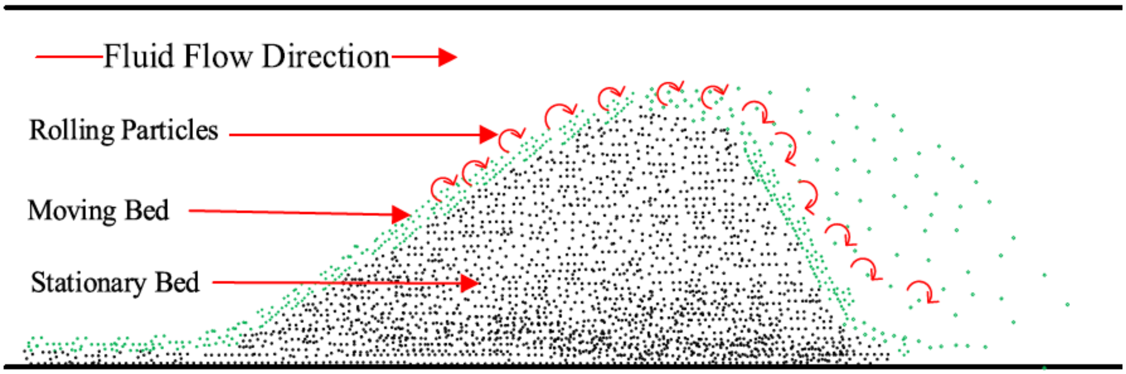


Figure 4—A graph illustrates movement of cutting dunes in a horizontal well bore section (Huque et al. 2021).

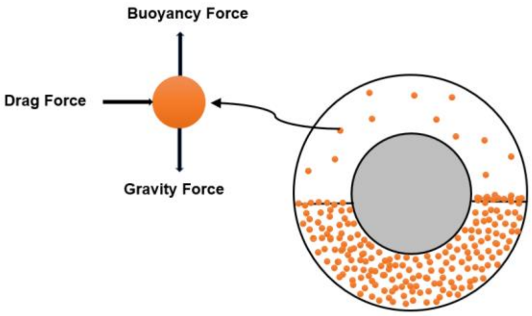


Figure 5—Principal forces acting on drill cuttings.

One of the main factors which are related to the posed extra challenges is the well profile of deviated and horizontal boreholes. A directional well profile is commonly referred to the projected well trajectory from the surface to the final drilling depth. **Figure 6** shows the geometric projections of common deviated and horizontal wellbore profiles.

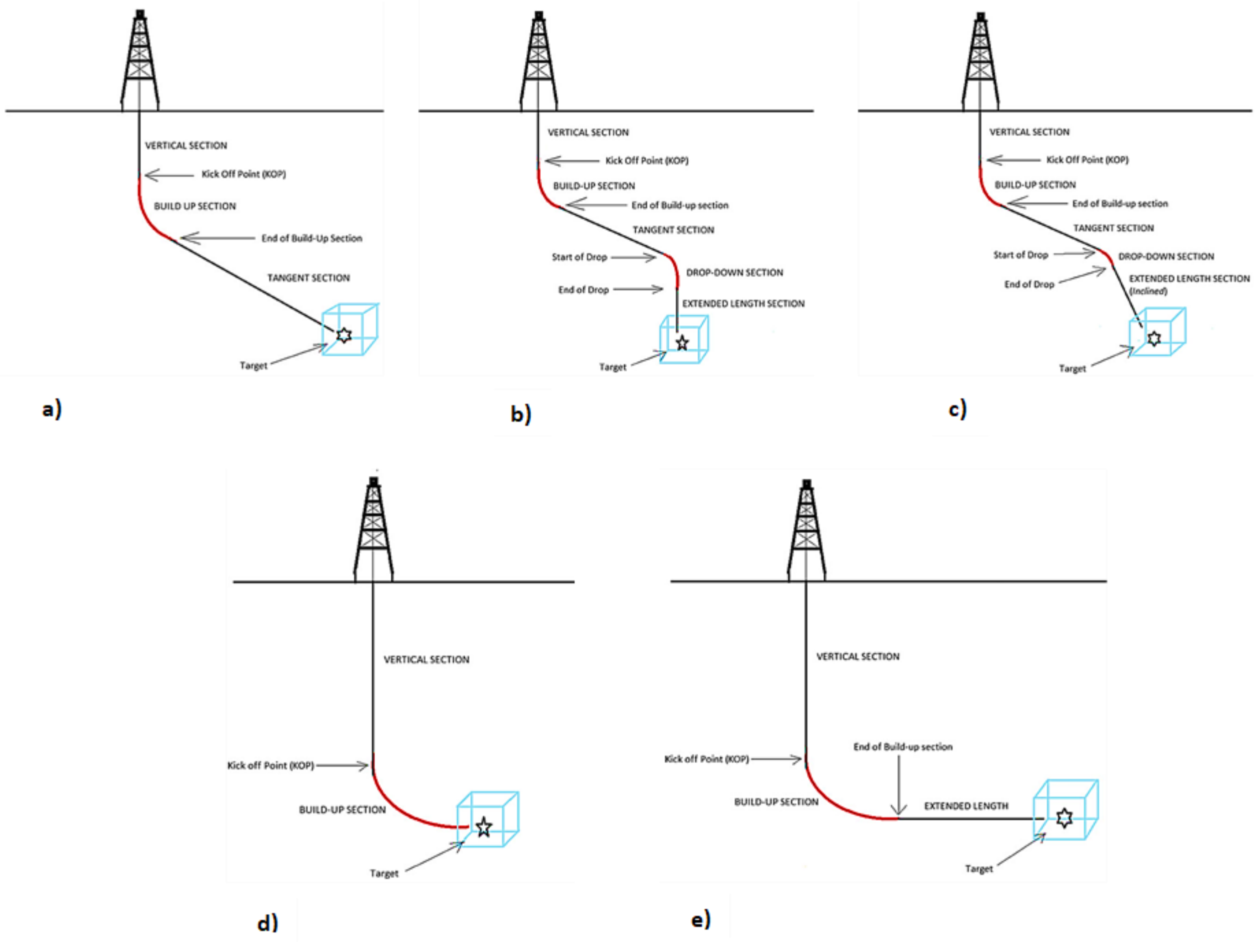


Figure 6—Deviated and horizontal wellbore profiles in vertical projection views: a) (J-shaped) two interval profile; b) (S-type) three interval profile and final drop-down segment; c) (Modified S-type) four interval profile with extended length section; d) (Continuous build up) two interval profile with final build up section; e) (Horizontal well) three interval profile with extended length section (Mukherjee and Banik 2023).

By gravity, drilled cuttings are carried by drilling fluid through the vertical section (lower than 30º) of J-shaped wellbore profile with reasonable free movement. But in bent sections, cutting transport becomes more difficult due to direction alterations and exerted centrifugal forces (Sun et al. 2013; Zhu et al. 2021) (**Figure 6a**). For slightly inclined wells between (30º-60º inclination angles) in (S-type) and (Modified S-type) profiles (**Figures 6b** and **c**) cutting transport mechanism is comparable to that of the (J-shape) profile. Nevertheless, cuttings transport becomes more challenging due to less gravitational force acting on the cuttings in the bended sections and a greater drilling fluid flow rate required to carry the cuttings up to the surface (Sun et al. 2013; Yeo et al. 2021).

Figures 7 show curved lateral and horizontal wellbore profile (inclination reaches 90º) where cutting transportation is typically more complicated in these types of profile. In these wellbore profiles, cuttings must resist many direction changes as well as absence of gravity forces in horizontal sections. For effective cuttings transportation in such profiles, high drilling fluid flow rates and suitable HC accessories/BHA are required (Piroozian et al. 2012; Al-Shargabi et al. 2024). As the well profile gets more complicated, the transportation of drilled cuttings becomes more difficult, and HC process will be a more challenging aspect. According to Al-Rubaii et al. (2023), there are recognized classes of borehole zenith angles that influence how far cuttings can be transported and sufficient HC state can be achieved. Depending on the zenith angle, drilling fluid reacts differently during the removal of drilled cuttings (Figure 7). Cuttings are efficiently carried by drilling fluid flow with no cuttings built up at zenith angles between (0º-30º) at noticeably greater velocities (zone-1). The deposition of cuttings is a phenomenon at zenith angles higher than (30º). The deposited cuttings rise in the shape of dunes on the cuttings/drilling fluid contact surface in turbulent mode (zone-2), but at lower velocities (zone-4), they are combined upward as a single mass. The optimal condition for cleaning the cuttings from the borehole are those found in (zones-1 and 2). Given that there is no cuttings upward movement at low flow rates as in (zone-5) class ensures the difficulty of cutting outflow as zenith angles higher resulting in lower annular flow velocities (Khosravanian and Aadnøy 2021; Al-Rubaii et al. 2023). **Table 1** presents a summary of cutting transportation and HC models in the literature.

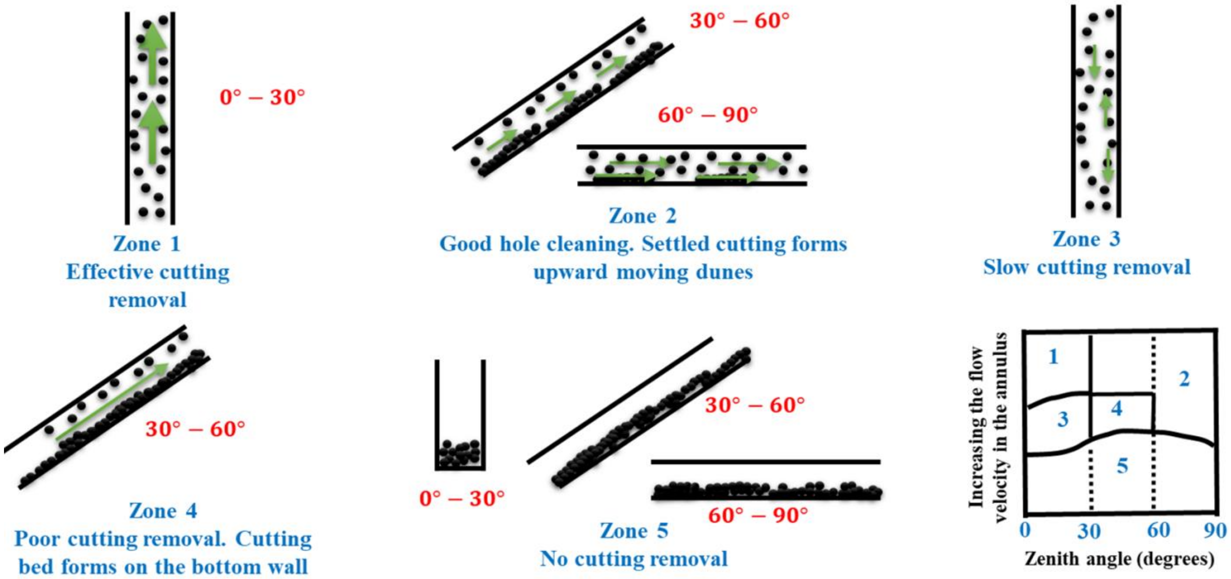


Figure 7—Cutting transport mechanism in the annulus for various zenith angles and flow velocities (Al-Rubaii et al. 2023).

Table 1—An overview of the key findings from all the most fruitful research on HC.

Methodology	Study	Objective	Studied Parameters	Application
Two layered models	**(Doan et al. 2003)**	Modeling critical V_T in underbalanced drilling.	Pressure, cuttings concentration, bed height, and cuttings velocity.	Underbalanced well drilling.
	(Li et al. 2004)	Numerical solution of cuttings transport.	Pressure drops, cuttings bed height, and V_T.	Deviated wells.
	(Adari et al. 2000)	Modelling cuttings bed height and the bed erosion time.	Drilling fluid properties and flow rates.	Highly deviated and horizontal wells.
Three layered models	(Becker et al. 1991)	Correlations for drilled cuttings Transport.	Qualitative analysis of cuttings removal.	Directional well drilling.
	(Peden et al. 1990)	Comprehensive experimental investigation of drilled cuttings Transport.	Cuttings transport efficiency, annular size, deviation angle and pipe eccentricity.	Deviated wells.
	(Han et al. 2010)	Cuttings transport modeling in a slim wellbore.	Cuttings V_T, pressure drop and cuttings concentration.	Slim hole drilling.
	(Guo et al. 2010)	Modeling cuttings transport performance in extended reach wells.	Equivalent circulating density (ECD) and cuttings bed thickness.	Extended reach wells.
	(Kamyab et al. 2016)	Experimental and numerical simulation of cuttings transportation.	Reynolds number and particle sphericity are employed to calculate cuttings slip velocity.	Coiled tubing drilling.
	(Tikhonov et al. 2023)	Explicit numerical solution and comparative analysis for cuttings transport in oil wells.	Flowrates, fluid rheology, well inclinations, and pipe eccentricity.	Oil deviated wells.
Numerical and experimental modeling	(Heydari et al. 2017)	Deep analysis of the eccentricity effect.	Axial velocity and cuttings volume fraction.	Horizontal drilling.
	(Shao et al. 2020)	Cuttings transport modeling using Computational Fluid Dynamic-Discrete Element Method (CFD-DEM).	Cuttings volume fraction, cuttings velocity, and shear stress.	Coalbed methane drilling.
	(Wang et al. 2021)	Cuttings transport modeling using CFD-DEM for hydraulic pulsed jet technology.	The influences of pulse jet velocity, amplitude, and frequency on hydrodynamic characteristics.	Horizontal drilling.
	(Shirangi et al. 2022)	Development of digital twins for drilling fluids.	Local velocities for HC and rheology monitoring.	HPHT drilling.
	(Chowdhury and Hovda, 2022)	Experimental investigations on cuttings transport using exploratory data.	RPM, drilling fluid flow rates, drilling fluid viscosity and eccentricity.	Vertical and deviated wells.

Employed Drilling Equipment/Assemblies for Improving HC. Drill cuttings have a propensity to fall onto the low side of the bore hole with increasing inclination of the wellbore. Since the drill collars will likewise incline to fall against the low side of the hole, a persistent accumulation of cuttings will raise the possibility of acquiring stuck pipe. Drill collars are thick-walled tubulars utilized at the bottom of the drill string. Their primary function in the drill string is to apply an axial force required to move the drill bit forward through the formation. However, they can also become stuck in the poorly cleaned bottomhole sections of the wellbore. This emphasizes the need of selecting a drill collar with optimal weight and stiffness during directional drilling operations (Lyons et al. 2021; Al-Shargabi et al. 2024). When using logging equipment or liners, a buildup of cuttings will also result in issues. However, various more technical downhole equipment and accessories could be used for the purpose of efficient cutting removal and safe drilling operations. In addition. cuttings that were carried out of the annulus should be thoroughly filtered and removed at the surface before being recycled again. It is crucial to employ solids management tools like effective mud cleaners, hydro cyclones, and shakers for recycling drilling fluid solids control (Inglis 1987).

Bottom hole assembly (BHA) is the set of equipment that is used to create the desired wellbore trajectory between the drill pipe and the bit **Figure 8**. BHA has evolved over time from one or two basic drill collars to a very sophisticated array of equipment that stack up above the bit at a height of around 500 to 1000 ft. The primary components of BHA are the drill collar and additional specific accessories such as stabilizers, eccentric tool joints, centralizers, rotary steerable system (RSS), reverse circulation subs, hole openers, and down hole motors may occasionally be included to assure effective HC conditions. The eccentric tool joints can assist in mixing up any deposited cuttings and restore them to the main flow stream while rotating the drill string.

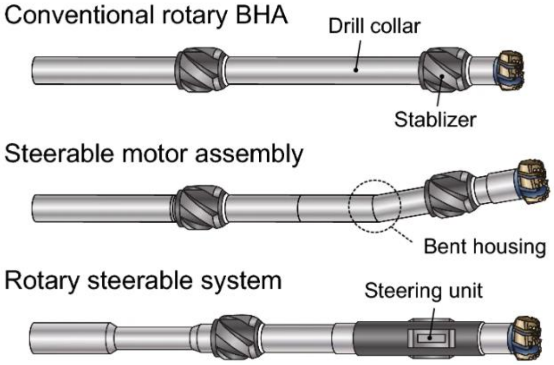


Figure 8—Schematic illustration of conventional, steerable and rotary BHA (Chen et al. 2019).

Directional drilling may be optimized with the use of rotary steerable drive system (RSDS). As seen in **Figure 9**, RSDS can reduce drag caused by the drill string sliding due to rotation and increase the weight on bit (WOB) gearbox efficiency. This lowers the chance of sticking and improves rate of penetration (ROP) while also achieving improved HC (Downton et al. 2000; Ma et al. 2016). Whereas down hole motors are powered by pumped drilling fluid to create mechanical rotation using rotor part. For drilling an intended depth interval, this rotational motion is given to a drill bit attached to the motor. They aid in preventing obstacles and raising ROP in wellbore deviations (Islam and Hossain 2021).

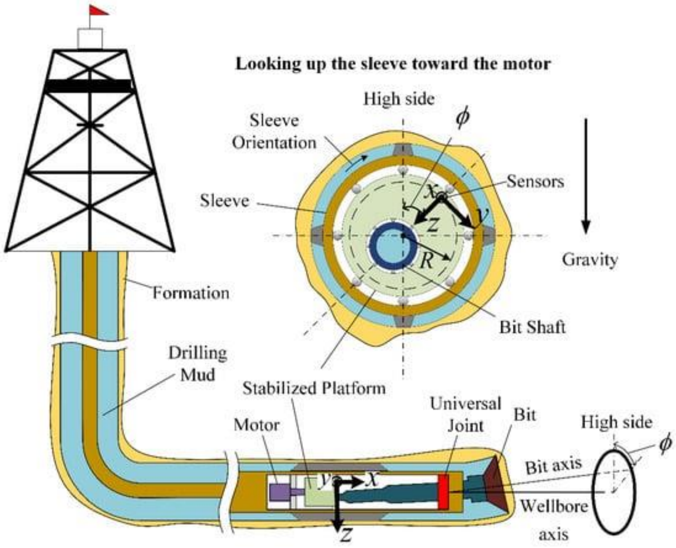


Figure 9—Schematic illustration of RSDS tool (Wang et al. 2018).

To transfer cuttings off the side of the borehole and redirect flow from the drill string into the annulus, reverse circulation subs can be assembled as part of the BHA. A hole opener is an assembly attached onto the drill string and is used to drill pilot holes at predetermined depths, producing larger diameter holes for increased wellbore stability and productivity. Most hole openers can be screwed into bit subs or near bit reamers since they feature standard pin-up connections (Rehm et al. 2012). As in **Figure 10**, The mechanical process of back reaming consists of pumping involves rotating the pipe and pulling it out the hole. However, HC may suffer from the purported benefits of back reaming for cuttings transfer (Chen et al. 2023; Zhu et al. 2023).

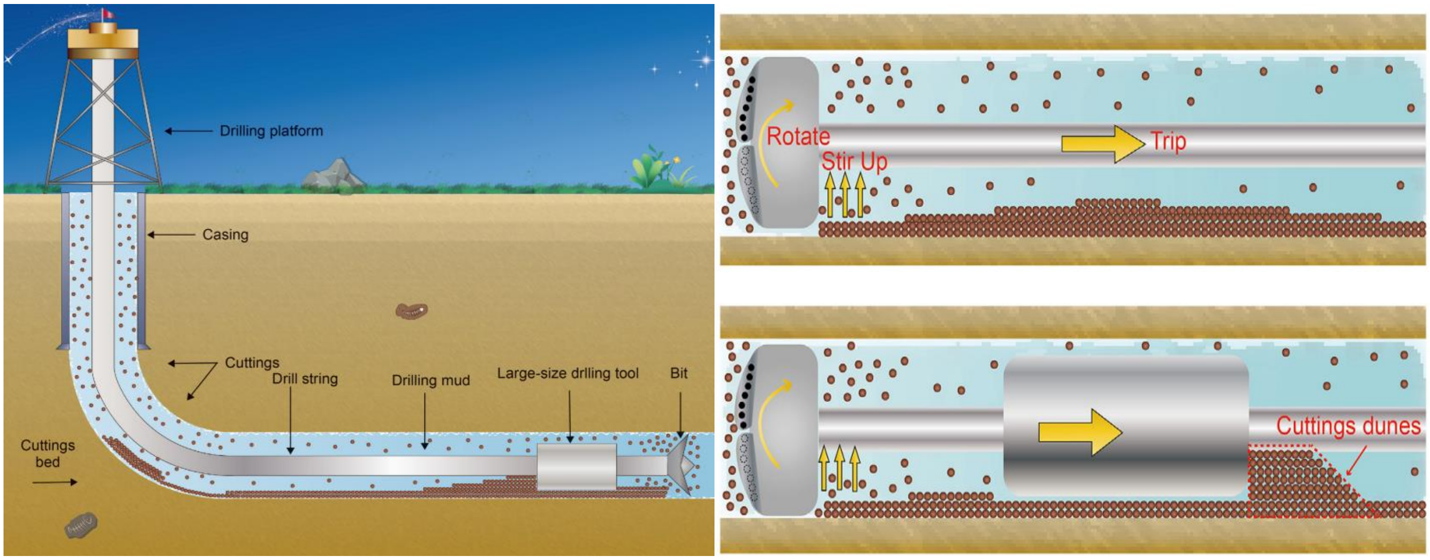
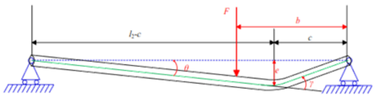
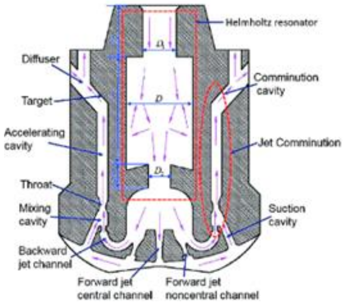
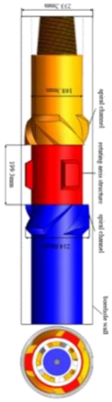
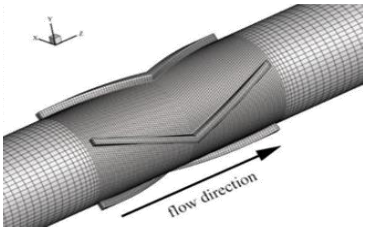
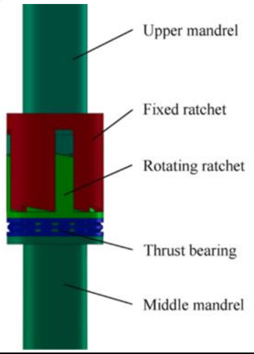


Figure 10—Back reaming process in horizontal well section (Chen et al. 2023).

A drilling stabilizer is a component of BHA installed in drill string. It mechanically stabilizes the BHA in the borehole to prevent unintended sidetracking, vibrations, and to guarantee the efficiency of the HC. Using drilling stabilizer significantly enhances cutting transport and, in turn, the HC process in deviated and horizontal wells (Tang et al. 2021). **Table 2** highlights implemented some of novel BHA designs and technologies for improving HC efficiency in directional drilling operations.

Table 2—Summary of literature work on various innovative BHA studies and technologies for better HC.

Descriptive tool shape	Study	BHA Tool	Methodology	Contribution in HC improvement
	(Liu et al. 2019a)	Bent-housing positive displacement motor (PDM)	The mechanical model of BHA with bent-housing PDM was developed utilizing the Timoshenko beam theory. The computed formulas for bit side force (BSF) and resultant steering force (RSF) were derived.	The findings indicate that the rotating speed of the drill string has a substantial impact on steering ability. The average BSF grows with drill-string rotating speed, whereas the RSF first climbs and then declines. Reduce drill string drag for better HC.
	(Liu et al. 2019b)	Pulsed mill bit (PMB)	Implementing designs including natural frequency of the Helmholtz resonator, ideal flow rate, drilling fluid flow velocity in the forward jet channel, critical cutting impact velocity, and minimum accelerating cavity length.	Offered a novel way to improve HC utilizing the pulse jet mill technology and a new kind of bit known as the.
	(Chen et al. 2022)	Vertexing cuttings removal tool (VCRT)	An effective vertexing cuttings removal tool (VCRT) has been designed and its cuttings removal process has been studied using CFD simulation technology.	When using VCRT during slide drilling, the average cuttings volume fraction is 59% lower than when using standard drill pipe and 26% lower than when using conventional cuttings removal tool. When using VCRT during rotary drilling, the average cuttings volume fraction is 78% lower than when using traditional drill pipe.
	(Zhou et al. 2022)	V-shaped HC tool	The effect of blade rotational speeds, fluid consistency coefficient, and blade helix angles on the HC effect are explored using numerical modelling.	It was discovered that the initial swirl intensity rises as the rotating speed increases. The HC performance was higher when the helix angle ranged from 10 to 20 degrees.
	(Tang et al. 2021)	Remotely adjustable stabilizer	An adjustable stabilizer with two distinct diameters is developed, and the drilling mud pump can be turned on or off to regulate each condition.	By installing an adjustable stabilizer, the drill bit lateral force and the borehole trajectory may be adjusted. This is achieved by altering the relative position between the drill string center line and the borehole center line.

In an ER oil well, Petrie and Doll implemented a continuous circulation system (CCS) to regulate the bottom hole pressure and mitigate ECD. To guarantee continuous circulation even when making connections, CCS is a drilling tool that is inserted in the drill string with each stand. By never turning off the pumps, continuous circulation over each connection improves the management of equivalent circulating density (ECD), which controls the bottom hole pressure on the well and prevents equivalent static density (ESD) from ever occurring in the wellbore. Consequently, cuttings are kept moving out of the wellbore by constant circulation, which minimizes or completely avoids the time needed for circulation of high angle sections prior to connecting a drill pipe or tripping out the well (Petrie 2021).

Factors Affecting HC

This section thoroughly discusses and sheds light on the most effective parameters on HC efficiency while drilling deviated and horizontal wells, which includes drilling operational, rheological, geometrical and HC direct indicator parameters.

Effect of Pipe Hole Eccentricity on HC. The drill pipe is considered completely eccentric if it lies against the inside diameter of the enclosing pipe or hole and concentric if it is exactly centered in the outer pipe or hole (**Figure 11)**. Accordingly, the numerical findings of Heydari et al' study (2017) showed that drill pipe eccentricity could enhance cuttings accumulation in deviated annuli**. Figure 12** shows CA at effective ROP of 20 ft/h and various eccentricities for varied flow rates of 300, 400, and 500 GPM, but the same. Heydari et al. (2017) indicated an obvious fact that the CA will drop with increasing fluid flow rates. Nevertheless, Figure 12d proves the fact that quantity of cutting phase settling depends more on downward eccentricities than it does on upward eccentricities. Accordingly, modest rotation of the drill pipe causes sharp decrease in the quantity of cuttings buildup, indicating that rotation is required in horizontal situations, particularly in those with higher eccentricities (Heydari et al. 2017).

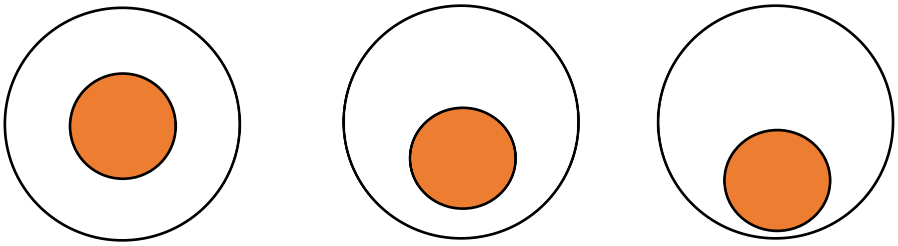


Figure 11—Concentric and eccentric annulus definition, a) ε = 0 annulus; b) ε = 0.2 annulus; c) ε = 0.4 annulus (Heydari et al. 2017).

Pipe eccentricity has little influence on HC for both turbulent and laminar flows at inclination angle ranges (0º-55º) (Okrajni and Azar 1986). In contrast, at greater inclinations (55º-90º), the effect will be more obvious. The eccentricity divides the flow cross-section into two regions: broad and narrow. With drill pipe rotation, the fluid moves in a helical pattern from the narrow stationary region to the high velocity broad region. However, Saasen and Løklingholm (2002) revealed that drilling fluid flow causes alternate flow velocities, which increases frictional pressure losses through the eccentric annulus.

Peden et al. (1990) stated that eccentric annulus with wider area at the bottom and a narrow area at the top could improve cuttings transport mechanism. However, drill pipe eccentricity has a negative effect on cuttings transport in inclined and horizontal wellbores (Walker and Li 2000; Duan et al. 2010). Additionally, annular CA steadily increases with increasing the degree of eccentricity, resulting in a cutting bed that causes poor HC conditions. However, the four-lobed drill pipe has better effect on HC performance in the annulus that do not cause severe cuttings deposition. Frictional pressure drop is lower in an eccentric annulus than in a concentric annulus, which affects fluid flow and velocity distribution especially in deviated wellbores. For Newtonian fluids, this divergence is more notable (Erge et al. 2015; Al-Shargabi et al. 2024).

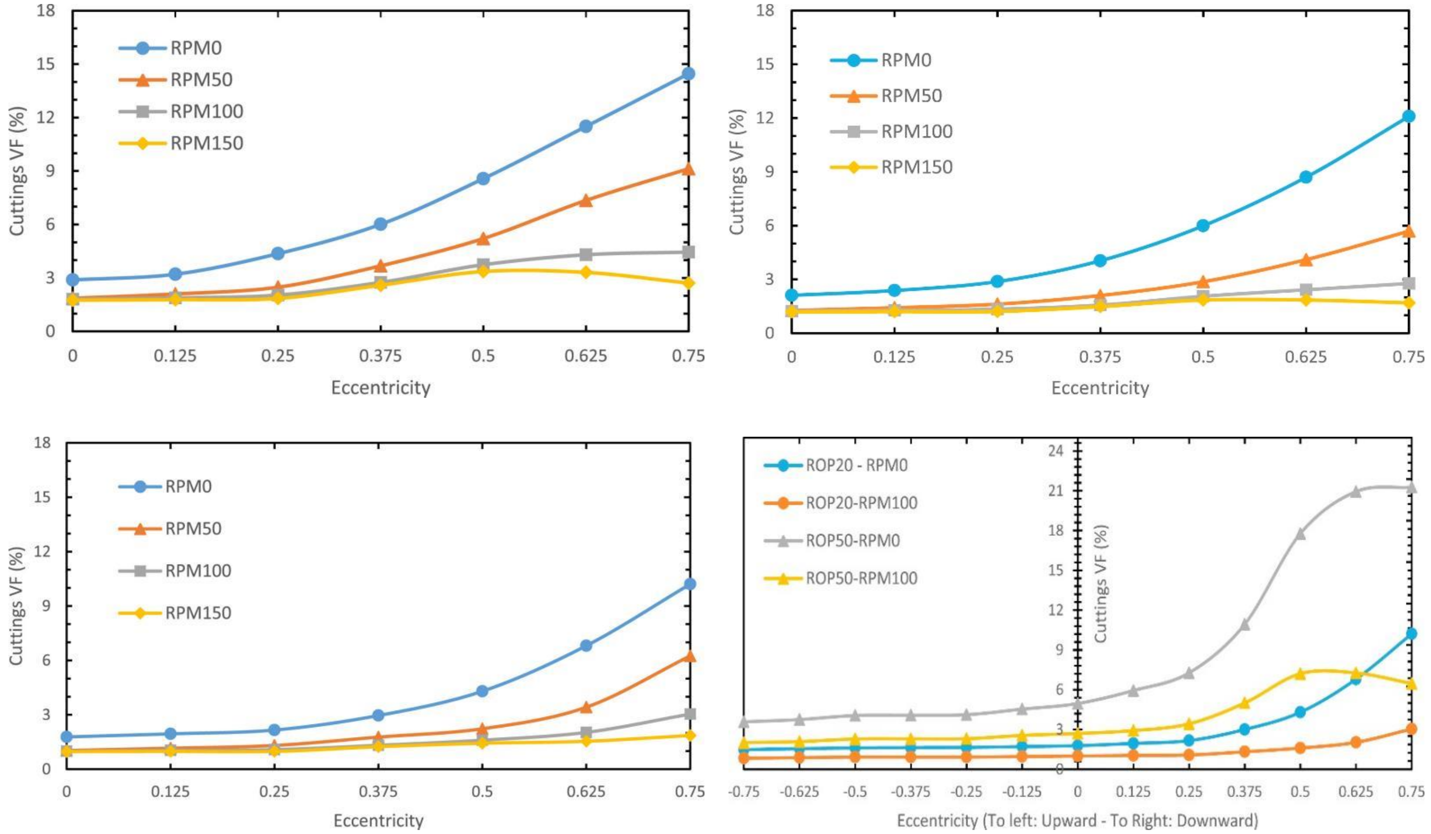


Figure 12—Cuttings concentration and pressure drop for various eccentric annuli: a) flow rates of 300 gpm; b) flow rates of 400 gpm; c) flow rates of 500 gpm; d) Impact of both upward and downward eccentricity on cuttings buildup (Heydari et al. 2017).

Kerunwa et al. (2021) recorded that ECD decreases with increasing eccentricity. Further, the drill pipe eccentricity may depress annular pressure losses. Furthermore, annular pressure losses are profoundly impacted by drilling fluid, with a 50% reduction anticipated in all eccentricity situations examined. More representative matches are made for the estimate of annular pressure losses using the Hershel Bulkley fluid model, particularly in horizontal and ER wells (Kerunwa et al. 2021). Saad et al. (2024) developed a generalized statistical model to predict CA and assess HC efficiency during deviated hole drilling. They demonstrated annuls velocity profiles under various presumed eccentricity degrees (0, 0.4, 0.8) using dimensionless data based on the Buckingham Pi theorem. In their work, the influence of eccentricity and cuttings concentration on the velocity transport ratio (VTR), carrying capacity index (CCI), and equivalent circulating density (ECD) have been studied in detail as the annulus deviates from concentric to eccentric, leading to suggested ranges for deviated hole drilling regarding inclinations up to 65° of (13-15), (0.5-1), and (0.8-1) lb/gal for eccentricity ranges (0, 0.4, and 0.8), respectively.

Effect of Drilling Fluid Density and Rheology on HC. Density is an important variable which influences the drilling fluid carrying capacity index. Drilling fluid density aids not only in conveying the cuttings, but also in supplying the pressure necessary for formation fluid control. Drilling fluid density has a significant effect on HC, with or without pipe rotation. The density of drilling fluid is vital for maintaining mechanical wellbore stability in cases of shale caving or sloughing, as well as for balancing the drilled hole sections and achieve efficient HC

(Al-Rubaii et al. 2023). Density and viscosity are interconnected fluid characteristics which can affect the behavior of the moving fluid. For instance, a drilling fluid viscosity, which describes the inter-resistant of the fluid to flow, can affect the velocity of the fluid flow through a pipe or annulus. A fluid with a high viscosity will flow more slowly than a fluid with a low viscosity, assuming all other factors stay constant. In a similar vein, the density of a fluid affects its flow rate. drilling fluids with high density require more pumping pressure to pass through pipes or annuli and cause flow rates to be delayed (Bilgesu et al. 2007). Hakim et al. (2018) and Zakerian et al. (2018) studied the efficiency of polyethylene and polypropylene beads in the transportation of drill cuttings in a horizontal wellbore.

Dense cuttings may result in severe cutting bed and pressure drop leading to mud resistance to flow. After then, (Yeu et al. 2019) investigated the cuttings lift efficiency utilizing low- and high-density polyethylene beads at various hole angles. To better investigate the influence of polymer beads on HC, their findings demonstrated that both types of beads outperform the basic mud in terms of HC efficiency. Low-density polyethylene beads, on the other hand, outperformed high-density polyethylene beads in cutting removal out of. Suspension of cuttings in the drilling fluid has less occurrence probability at high mud flow rates. Furthermore, effective drilling fluid density due to cuttings decreases at higher mud flow rates (Kerunwa, 2020). Additionally, high mud flow rates may result in greater pressure loss, which increases ECD. Badrouchi et al. (2022) investigated how CA could affect ECD during drilling. After comparing predicted ECD with and without CA effect, the authors concluded that the CA has an essential impact on the ECD in the annulus.

Rheology is the study of fluid flow behavior, and it is an important property for achieving efficient HC state. **Figure 13** displays the four primary models: Newtonian, Bingham plastic, pseudoplastic, and dilatant models. Drilling fluid rheological curves are useful for accessing CA, ECD, and hydraulic parameter optimization (Liu et al. 2021). To assess cutting transport, Bingham plastic models are used to estimate yield point (YP) as the minimum shear stress needed to start a flow and plastic viscosity (PV) as the flow resistance of the drilling fluid. This value is essential for figuring out how the fluid can transport cuttings and keep holes clean during drilling operations (Blkoor et al. 2022; Al-Rubaii et al. 2023). More significantly, Hussaini and Azar (1983) first suggested (YP/PV) ratio which is a fluid rheology characteristic obtained from the Bingham plastic model, as a metric to evaluate the efficacy of solids in drilling fluid hole-cleaning capability. Their results showed that, unrelatedly to the inclination angle, a higher YP/PV results in better HC (Al-Rubaii et al. 2023). According to (Mahmoud et al. 2020) effective HC can be ensured by drilling fluid characteristics including YP of the drilling fluid, which in highly deviated wells should be raised significantly. It is recommended to utilize a YP/ PV ratio higher than 1.

An empirical study made by Ozbayoglu et al. (2009) revealed that drilling fluid density had a moderate effect on cutting bed accumulation. Besides, inertial and buoyancy forces are affected by fluid density. They found that Reynolds number and lifting force increase simultaneously with the increasing of drilling fluid density, leading to prober HC. Further, they revealed that low-viscous thin fluids are more successful in removing cuttings from horizontal and deviated wells. Additionally, they stated that low viscous fluids enable the formation of turbulence flow regime at low flow rates which raises local fluid velocity near cuttings bed leading to better transport efficiency (Ozbayoglu et al. 2009). Annular fluid forms a spiral axial flow with the drill pipe resulting in an improvement in drilling fluid cuttings carrying capacity and HC efficiency. Moreover, A standard circular drill pipe that has been properly modified may provide greater HC performance. Additionally, under drill pipe rotation, a more violent swirl motion can be created (Yan et al. 2020).

Drilling fluids under HPHT experience severe degradation in their density, rheology, and thermal stability in both static and dynamic environments. Attaining the targeted levels of ECD, lubrication, and viscosity can be challenging, especially when the drilling fluid window gets narrow, and the fluids are tainted by formation of inorganic salts and acid gases (H_2S and CO_2) (Gautam et al. 2022).

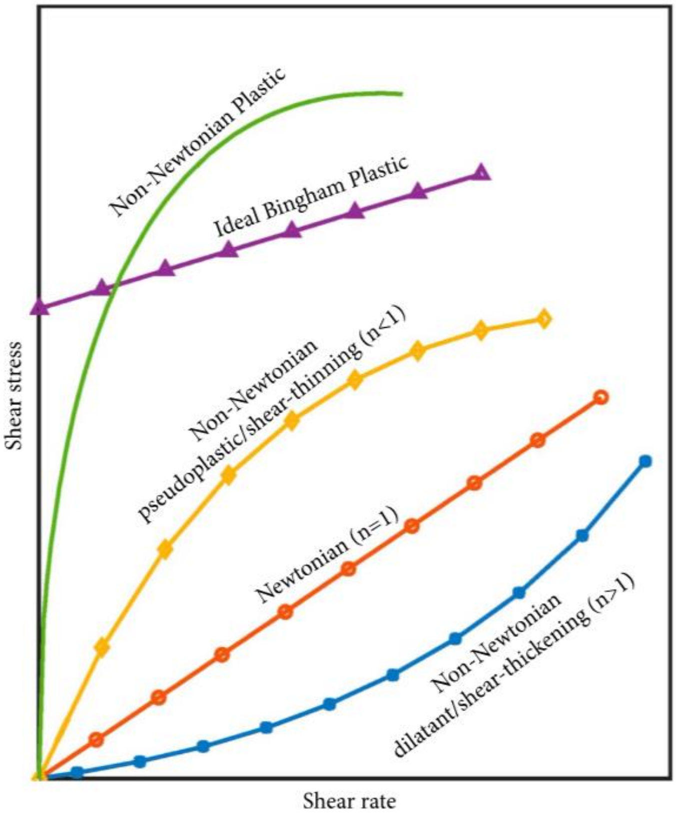


Figure 13—Curves of the four rheological models for different types of fluid (Liu et al. 2021; Al-Rubaii et al. 2023).

Effect of Drilling Fluid Sweep Efficiency on HC. Owing to the influence of hole inclination, the conventional drilling fluid effectiveness declines during deviated hole drilling. Cuttings settle down in deviated wells as the inclination angle increases, causing cuttings to accumulate on the low side of the hole. Both scenarios result in poor wellbore cleaning efficiency. Drilling fluid is one of the primary aspects that may be regulated by modifying its rheological properties properly. To maximize cuttings removal from the hole, many additives could be added with conventional mud systems to create new formulations with better sweeping efficiency (Bulgachev and Pouget 2006; Lyu et al. 2019). **Figure 14** summarizes most of the previously reviewed fluid types and base additives of each sweep in deviated hole drilling.

Previous field applications reported that, oil-based mud (OBM) has been more effective in removing cuttings in deviated wells than water-based mud (WBM) in terms of better sweeping efficiency and mud rheological qualities (Pratap et al. 2006; Song et al. 2016; Werner et al. 2017). In contrast, laboratory studies indicated that the effect of pipe rotation made no difference between OBM. However, in the absence of pipe rotation, oil-based fluids performed better than water-based fluids (Werner et al. 2017). Recent developments in the study of drilling fluids have demonstrated that problems related to shale gas drilling have been addressed by WBMs formulated using nanoparticles. Nanoparticles could prevent the transference of pore pressure in the shale formations by physically blocking the nanopores. Moreover, nano-silica particles have an exceptional light weight and high surface area to volume ratio that help cuttings to overcome cohesion and gravity forces by increasing drag and lift forces (Mahmoud et al. 2020; Mahmoud et al. 2021). Boyou et al. (2019) implemented an investigation into the effect of 14 nm nano-silica particle on the efficiency of cutting removal in highly inclined flow loop system at rotational speed up to 150rpm. Their findings indicated that nano-silica particles improved the performance of conventional WBMs regarding HC efficiency by more than 38% on average. They attributed this increase in HC efficiency to the resulted increase in colloidal interactions between the drilling fluid and cuttings caused by formulated nano-silica WBMs.

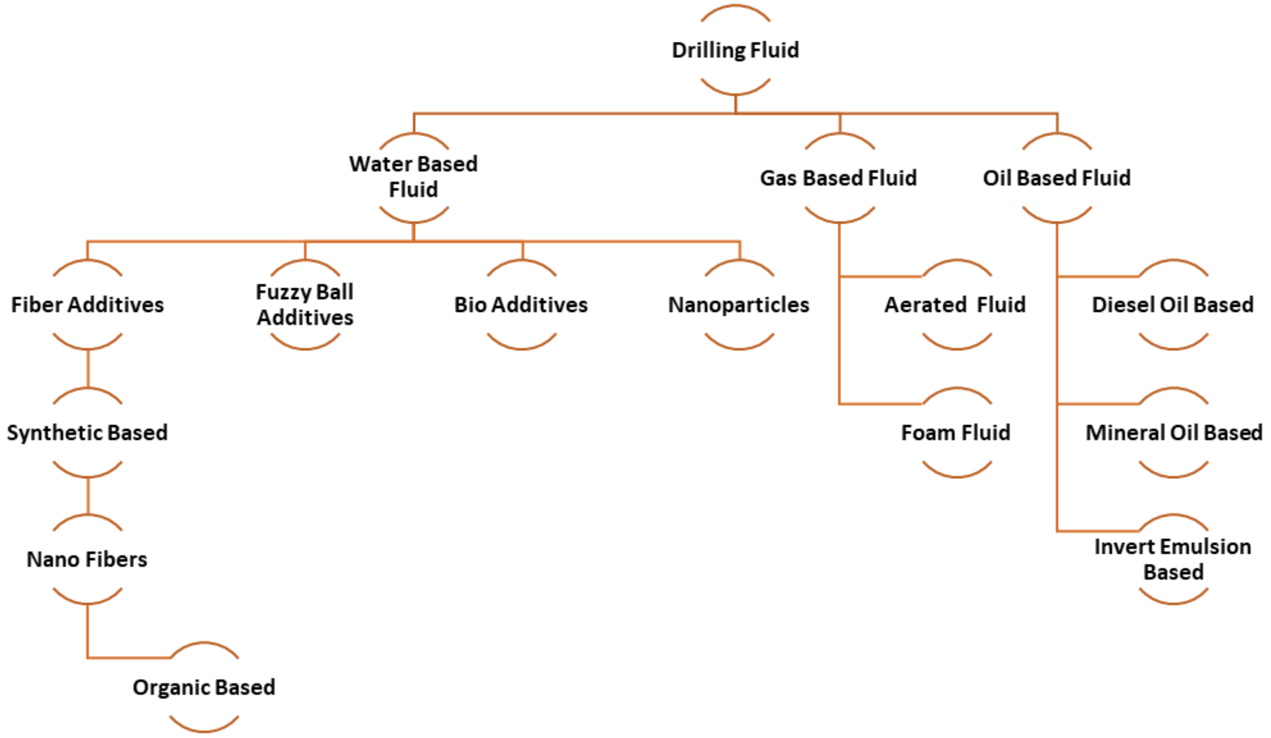


Figure 14—Drilling fluid types and base additives.

Increased bentonite contents lead to increased suspension, which can improve the cuttings sweep down the wellbore up to the surface but can result in frictional pressure losses. Deng et al. (2020) studied the effect of YP and PV in drilling fluids with different bentonite concentrations in complicated wells. They found that cuttings carrying capacity is influenced by plug width and yield stress, which both affect suspension in drilling fluid. For effective HC and ensuring safe energy consumption, borehole stability, cuttings sweep, and pressure management are essential (Deng et al. 2020). **Table 3** summarizes some of literature work that related to drilling fluid sweep efficiency and HC.

Anionic polymers work as a thinning agent by stabilizing the positive charges on the clay edge (charged bentonite) in the drilling fluid. For a typical WBM to have its desired characteristics, a certain amount of polymer-clay interaction is required. The process of clay particles adhering to one another through several kinds of mechanisms, including cation exchange, is known as flocculation. In HPHT conditions under both static and dynamic circumstances, temperature-induced flocculation and gelation can occur in bentonite in fluid over 300 °F, resulting in poorly controlled viscosity, sweeping efficiency and filtration loss behavior (Annis 1967). Besides being extremely susceptible to acidic pH, salinity, and salt contamination, clay under HPHT conditions also cause insufficient stabilization towards the reactive formations. Research has been concentrated on creating alternative fluid systems, or (clay-free fluid systems) that do not contain clay because of these drawbacks associated with its usage in formulation. Compared to a conventional bentonite-based drilling fluid, a clay-free fluid offers several inherent advantages, including (i) a quicker rate of penetration, (ii) greater HC capabilities, (iii) simpler fluid management, and (iv) improved wellbore stability (Galindo et al. 2015).

Figure 15 displays the total number of publications about HPHT drilling fluids over time. It illustrates how WBMs dominate other fluid systems, such as those that are oil and synthetic-based drilling fluids. Thus, choosing the right drilling fluid and additives in HPHT conditions is essential and has a big impact on how safely oil and gas wells are drilled. As a result, it is difficult to keep drilling fluid operating as intended under HPHT conditions at high pressure and temperature (Gautam et al. 2022).

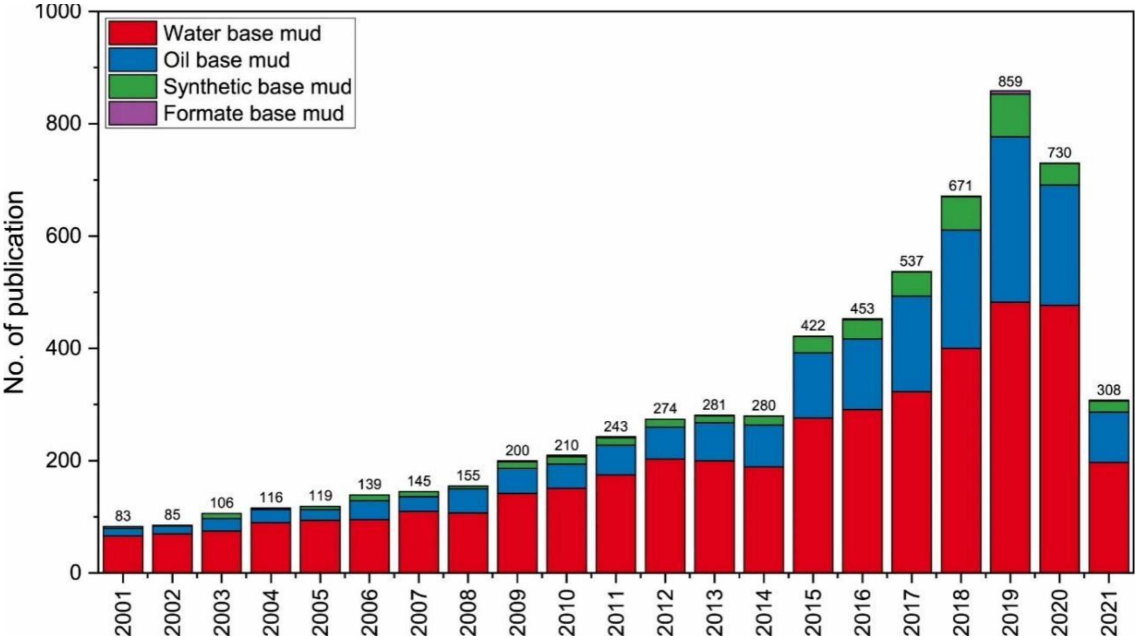


Figure 15—Records of publications for HPHT drilling fluid between 2001 and 2021 (Gautam et al. 2022).

Effect of Drilling Fluid Carrying Capacity on HC. One of the most important roles of a drilling fluid is its ability to carry cuttings underneath the drill bit up to the surface through the wellbore annulus. This is often referred to as the CCI of drilling fluid. As per API recommended practice on rheology and hydraulics, Bern et al. (2007) defined the term CCI as in **Eq. 1**,

$$CCI = \frac{(\rho_f)(K)(V_s)}{400000}, \quad (1)$$

CCI is considered as a measure to determine how well a mud system circulates cutting down the hole to the surface. Okon et al. (2015) demonstrated that their formulated synthetic-based mud showed promising CCI and HC potential as an effective drilling fluid. Correspondingly, Alawami et al. (2020) developed an intelligent model to calculate CCI as a real time measurement tool to assess ability of a mud system to circulate cuttings up to surface through the wellbore annulus. According to them, real-time automatic CCI calculations are accomplished by intelligent designed systems using rig sensors continually provide thousands of raw data combined with certain well data, including hole and casing sizes.

Table 3—Summarization of literature work on drilling fluid sweep efficiency and HC.

Study application	Authors	Results
Experimental application	**(Ahmed and Takach 2009)**	Despite having virtually comparable rheological characteristics, a fiber-containing sweep provides greater hole-cleaning capabilities than the base fluid. Using fiber additives decreases annular pressure loss.
	(Elgaddafi et al. 2012)	Fiber drag is affected by the particle's projected area, settling velocity, fiber drag coefficient, and fluid-particle density differential.
	(George et al. 2014)	Adding fiber to hole-cleaning sweeps enhances cuttings removal in inclined annulus, but only when the pipe is rotated. Fiber has only a little effect on cuttings bed removal when the annulus is horizontal, or the pipe is not rotated.
	(Song et al. 2016)	In comparison to the fluids with bigger and longer cellulose nanoparticles, the fluids with smaller cellulose nanocrystals had lower viscosity, YP, and gel strength, and the produced filter cakes had higher porosity and lower permeability. The arrangement of (CNPs) was critical in changing the fluid characteristics.
	(Sayindla et al. 2017)	WBMs and OBMs showed similar cutting removal efficiency with pipe rotation, while oil-based fluids are more efficient without pipe rotation.
	(Mahmoud et al. 2021)	Al2O3- and CuO- nanoparticle had a greater ability to improve mud qualities when utilized at low concentrations of 0.3-0.5 wt.%.
Field application	(Gao and Young, 1995)	The effectiveness of cuttings transport is determined by fluid characteristics, particularly with reacting shales. Pipe rotation with high-density mud improved cuttings conveyance substantially.
	(Cameron et al. 2003)	When combined with pipe rotation, lost circulation materials sweeps boosted the rate of cuttings return to the surface by up to 50%, resulting in significant gains in drilling rate.
	(Bulgachev and Pouget 2006)	Highest HC outcomes can be achieved by circulating combination tandem sweeps, which are low-viscous fiber sweeps treated with a sweeping agent followed by a treated or untreated high-density sweep.
	(Pratap et al. 2006)	Low viscosity synthetic OBM paired with a rotating system reduces horizontal drilling time and eliminates poor HC issues.
	(Werner et al. 2016)	At low temperatures, OBMs outperform KCl-WBMs in HC. The YP of the fluids is likely to have the greatest effect on static and low-flow conditions, whereas PV may be more important in high-shear area of the flow.
	(Lyu et al. 2019)	Enzymes with a 0.01% weight fraction can significantly modify the rheological characteristics of drilling fluid, resulting in considerable biological activity.

Effect of Annular and Cutting Transport Velocities on HC. To guarantee that the drilling fluid successfully removes the cuttings from the wellbore, its annular velocity (Va) must be higher than the cutting slip velocity (Vs). Furthermore, for excellent HC, smaller axial and radial Vs values are preferred. It is important to regulate these velocities appropriately to guarantee effective HC and successful drilling operations (Ramsey 2019). According to Boyou et al. (2019), the annular fluid velocity and rheological properties of the drilling fluid are thought to be the most efficient drilling parameters for preventing the formation of cuttings bed. Bern et al. (2003), detailed that cutting beds occur on the low-side of high-angle holes due to restricted annular velocity. Drilling cuttings are unlikely to be removed from the wellbore if the circulation rate is relatively low. As the flow rate increases, this cutting bed becomes increasingly undermined. Solid particles flowing across the bed interface form dunes or huge waves. This bed movement mechanism is a more visible characteristic of HC with low viscous fluids.

Critical transport velocity is defined as the minimal fluid velocity necessary to sustain a continual upward movement of the cuttings. Cuttings from the drill bit and other formation materials will fall into the wellbore at lower velocities than the critical transport velocity. Hence, annular flow velocity must be high enough for cuttings to be cleaned efficiently. Instead of depending just on the cuttings slip velocity (V_s) without any correlations, it is crucial to estimate HC in deviated and highly inclined wells in terms of cutting V_T (Sifferman and Becker 1992). As eccentricity increases, cuttings take longer to reach the surface due to a decrease in V_T. They also stated that V_T is a crucial parameter for preserving cutting upward mobility and preventing deposition or accumulation of cuttings inside the wellbore.

Effect of Drill Pipe Rotation on HC. Saasen and Løklingholm (2002) reported that secondary flow streams known as Taylor vortices can be caused by pipe rotation. Frictional pressure losses produced by these vortices enhance the shear tension on the cuttings bed surface. Hence, shear stresses generated consequently might gradually improve cuttings removal. Due to the created centrifugal and shear forces by rotating drill pipe, CA drops with the increasing of rotational speed, and this is consistent with the findings of (Ozbayoglu et al. 2012). At rotational rates of 50, 100, and 150 rpm, CA in the annulus of an elliptical drill pipe was reduced by 7.7%, 11.4%, and 14.2%, respectively, when compared to the circular drill pipe. This indicates that the faster the rotating speed, the better the elliptical drill pipe HC performance. The improvement of HC is greatly influenced by the dynamic behavior of the drill pipe.

Hongtu et al. (2021) studied the effect of drill pipe rotation on gas-solid flow properties using CFD-DEM simulation. As seen in **Figure 16**, the particle distribution in each of the three-bit fluid holes varied while the drill pipe was not rotating (0 rpm). All the particles entered the drill pipe, and the distribution of particles in the top fluid hole was comparatively steady. While all the particles in the lower bit fluid holes, most of the particles in the lateral fluid hole entered the drill pipe. A portion of the fluid hole particles entered the drill pipe via the inner wall of the fluid hole as the drill pipe started to rotate (between 50 and 200 rpm). The quantity of particles dropped from the side and lower fluid holes increased with rotational speed increasing. Furthermore, no particles fell from the top fluid hole at 0–100 rpm, but a minor amount fell at 150-200 rpm. The drill pipe rotation caused the falling particles to move in the opposite direction (Hongtu et al. 2021).

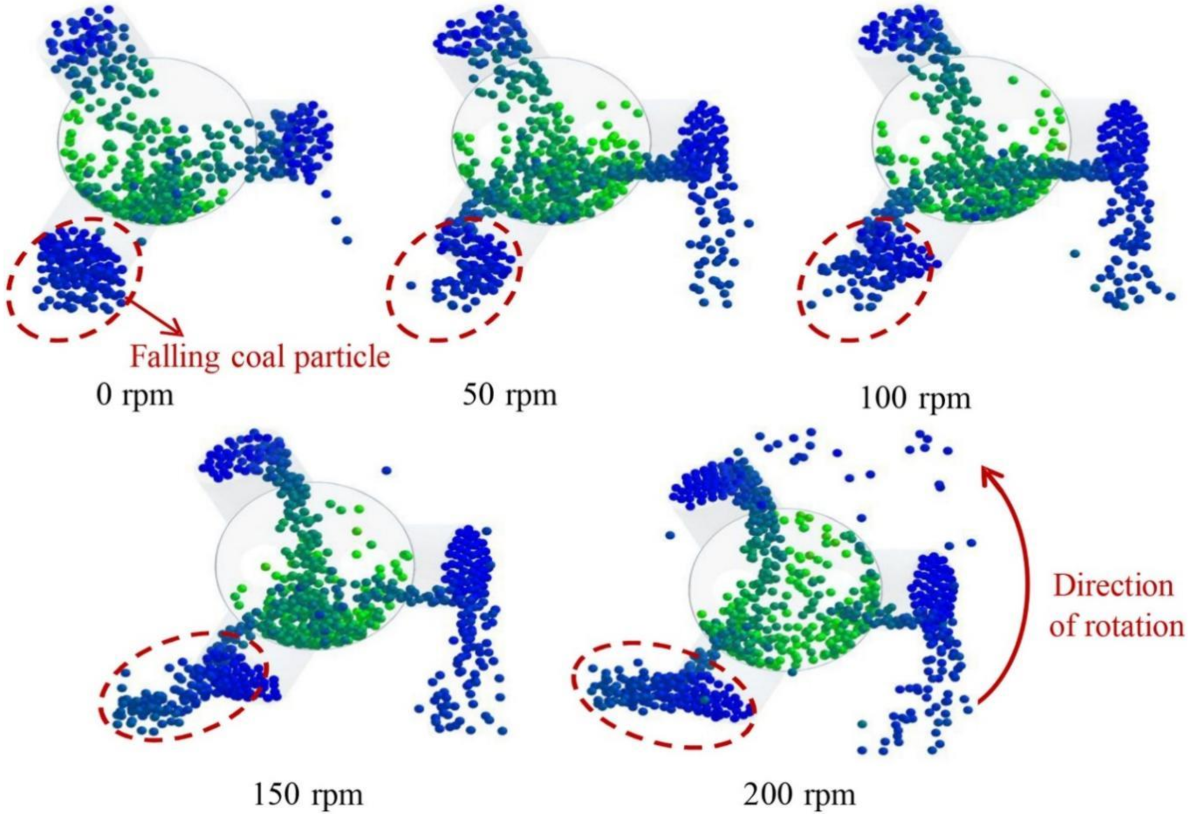


Figure 16—Pattern of particle flow through drill bit fluid holes at various rotational speeds (simulation run time 0.32s) (Hongtu et al. 2021).

Effect of ROP on HC. Cutting transport is greatly enhanced for deviated wellbore by optimizing ROP. Due to an increase in cuttings accumulation in the annulus, ROP values necessitate greater transport flow velocities (Nour et al. 2022). The efficiency of HC and cuttings transport are significantly increased by optimizing ROP. However, CA increases as ROP increases at a steady flow rate. To properly remove cuttings from the wellbore, higher hydraulic output is needed as the amount of cutting accumulation grows. Therefore, it is crucial to modify drilling fluid flow rate while drilling at high ROP. However, if HC efficiency is not increased by changing the flow rate or RPM; instead, it is typically wise to lower the ROP (Khosravanian and Aadnøy 2021).

To underline the significance of predicting ROP, it should be noted that excessive ROP application during the drilling process can result in inadequate HC and improper removal of drilling cuttings from the bottom hole to the surface (Al-Kaabi and Lee 1990). Furthermore, for proper removal of cuttings from the wellbore, higher hydraulic output is needed as the volume of cuttings grows. Therefore, ROP and mud flow rate need to be raised optimally to accommodate for the increase in cuttings volume. Nonetheless, it should be highlighted that raising the flow rate does not completely offset the effects of raising ROP (Bilgesu et al. 2007). Nevertheless, around 52% of the wells are drilled at rotational speed of less than 70 rpm and a ROP ranging from 5.3 to 32.8 ft/hr. This is not enough to clean holes successfully, especially if the hole diameter is more than 8.5 in (Al-AbdulJabbar et al. 2019).

Effect of Drilling Cuttings Characteristics on HC. The size and shape of cuttings are significant factors when studying HC since they are the material that is transported from the bottom of the hole to the surface. The drill bit used during drilling operations influences cuttings properties such as size, density, and shape. Smaller cuttings are easier to carry at all angles when using a low viscosity fluid (Peden et al. 1990). On the other hand, bigger cuttings are moved more efficiently using high-viscous fluid at low inclinations (0º-50º). The critical velocity required to carry up various cutting sizes is also affected by CA and pipe eccentricity (Walker and Li, 2000). Cuttings produced during the drilling process have a quantifiable density that normally falls between (2.4-2.8) ppg in terms of specific gravity. On the other hand, the drilling fluid specific gravity usually varies between 0.9 and 1.8. Because of this, solid particles produced during drilling tend to settle and accumulate inside the wellbore when there is no fluid circulation (Zhang et al. 2015).

Ramadan et al. (2003) concluded that, intermediate (0.76 mm) particles were found to be harder to remove than the fine and coarse particles. Yilmaz (2012) investigated the moving bed velocity of particles with a sphericity of 0.1 using the Discrete Phase Model (DPM) and the Rosin-Rammler size distribution. The results showed a small improvement in HC efficiency with higher particle sphericity using three different sphericity levels. Further, Fluid contact area grows with the increasing of cutting size, making it easier to apply drag and lift forces on particles (Ozbayoglu et al. 2009). Despite this, other research revealed conflicting findings.

Hakim et al. (2018) studied the efficiency of polyethylene and polypropylene beads in the transportation of drill cuttings in a horizontal wellbore. The cutting transport efficiency was measured for polyethylene and polypropylene beads with cutting sizes ranging from (0.5-4 mm) while the rig was simply fixed in the horizontal position. The results revealed that polymer beads enhanced HC efficiency, but that polypropylene beads outperformed polyethylene beads. Denser drilling cuttings resist fluid flow resulting in higher cutting deposition and annular pressure drop (Zakerian et al. 2018). Greater density drilling cuttings sometimes settle faster and need greater annular DF velocities to be properly removed from the wellbore.

Pedrosa et al. (2023) experimentally studied sand grains, or quartz, with an average size of 1.3 mm and an irregular shape to mimic the drilled cuttings, which are the most basic kind of down-hole rock formation. It was shown that the shear stress was not entirely stable throughout the pre-shear stages, exhibiting certain peaks and instabilities, during the shear stress under confined normal stress data from all the samples. The most probable reason for this is the morphological impacts. Cutting shape can have a significant and powerful impact since quartz grains are not spherical, (Cleary 2008). So that shear stress charts would be smoother and less variable if the cutting grains are more spherical (**Figure 17**).

Effect of Hole Inclination Angle and Geometrical Effect on HC. In a field application, (Adari et al. 2000) rated the HC affecting parameters in directional drilling operations and found that the time required to effectively clean the wellbore rises with increasing the inclination angle. Mitchell (1995) discovered that the same variables that affect HC in a section with vertical holes also affect HC in sections with deviations and horizontal holes. The degree of inclination was the only significant factor affecting HC in deviated and horizontal sections. He concluded that Inclined geometries would result in a cutting bed and make drill cuttings more prone to settle. Accordingly, volumetric CA in deviated annuli would rise with the continuous formation of cutting bed. He came to the finding that in a laminar flow environment, directional drilling should be done at a moderate angle of 30° to 60°.

Tomren et al. (1986) stated that cutting beds are more common at hole inclinations higher than 40°, even at higher flow rates. HC in inclination ranges of 40° to 60° from vertical requires techniques and care to prevent excessive cutting bed formation (Hopkins and Leicksenring 1995). Above inclination of 60°, the cutting bed thickness practically remains constant. This implies that between 40° and 60° is the most undesirable hole inclination range for HC (Egenti 2014). The degree of inclination has an impact on the critical velocity and reaches its greatest value when the angle is equivalent to the angle of resting in the range of 75° to 90° (Bilgesu et al. 2007; Ramadan et al. 2003). Pandya et al. (2020) specified the effect of inclination angle on HC performance utilizing hole angle factor (G) in (rads) as in **Eq. 2**,

$$G = 1 + \frac{(\theta)(\pi)}{180}, \quad \ldots\ldots (2)$$

where θ is the measured inclination angle in degrees (°).

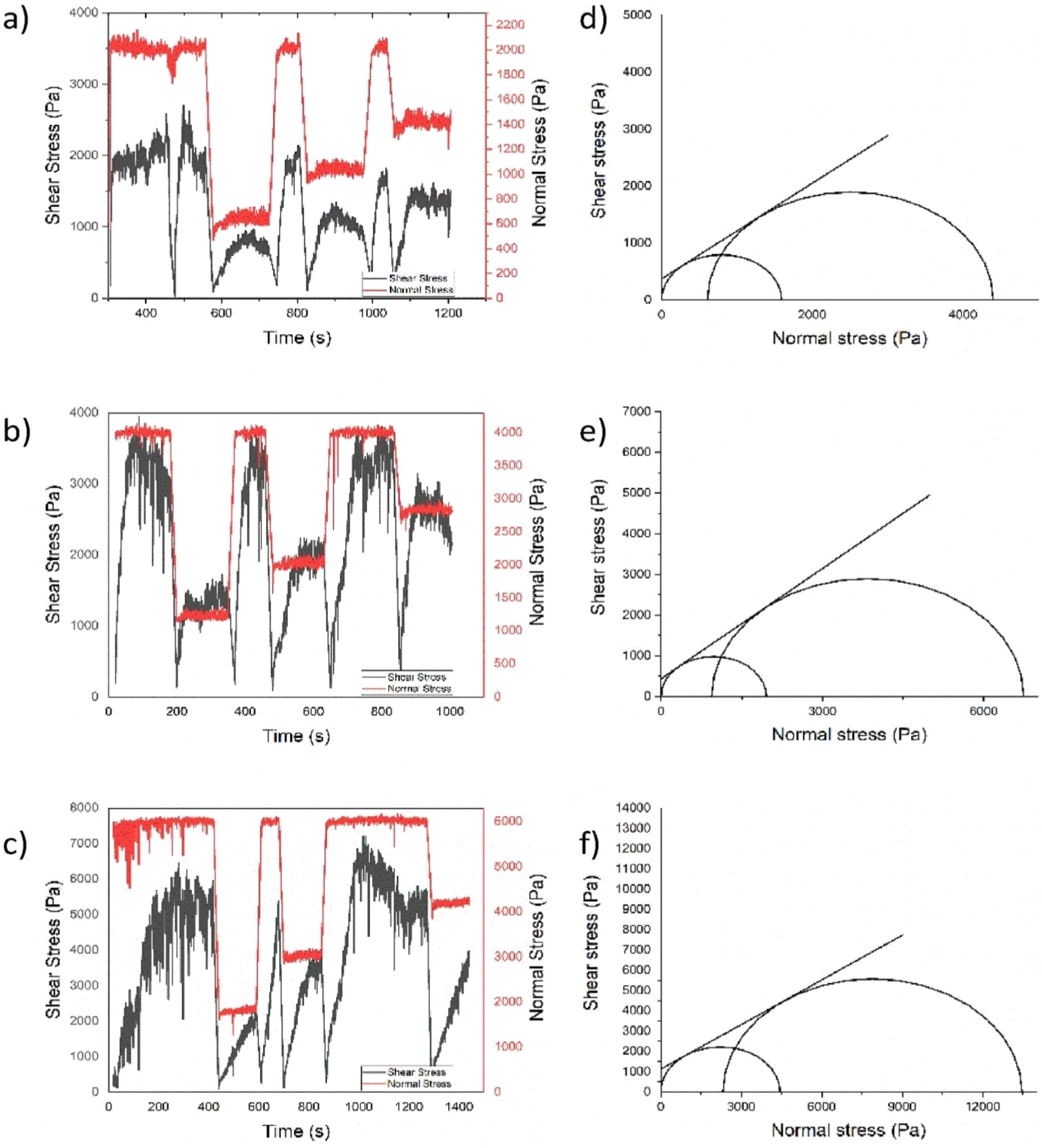


Figure 17—Charts of shear stress under normal stress confinement: a) 2 kPa, c) 4 kPa, e) 6 kPa and its obtained Mohr-Coulomb envelopes b) 2 kPa, d) 4 kPa and f) 6 kPa for sand wetted with OBM (Pedrosa et al. 2023).

Furthermore, Chen et al. (2007) measured the critical velocity of superior-grade foams and documented a rise in critical velocity in tandem with a decrease in foam quality. Prasun and Ghalambor (2018) revealed similar results based on modelling research and laboratory trials. As a result of the separation of gas and liquid phases caused by an increase in inclination angle, foam-based drilling fluid experienced a change in flow pattern. Increasing the foam quality improves the removal of the cuttings at velocities higher than the critical threshold.

Figure 18 exhibits an illustration of how hole inclination affects HC. Plotting of hole inclinations vs cutting transport performance (CTP) for a single velocity value and various liquid viscosities has been done for each curve. Rolling mechanisms are used for transportation at high angles when a stationary cuttings bed may occur.

A lifting device is used for transport in intermediate angles where a churning, moving cuttings bed may occur. Transport is determined by particle settling at nearly vertical angles (Piroozian et al. 2012).

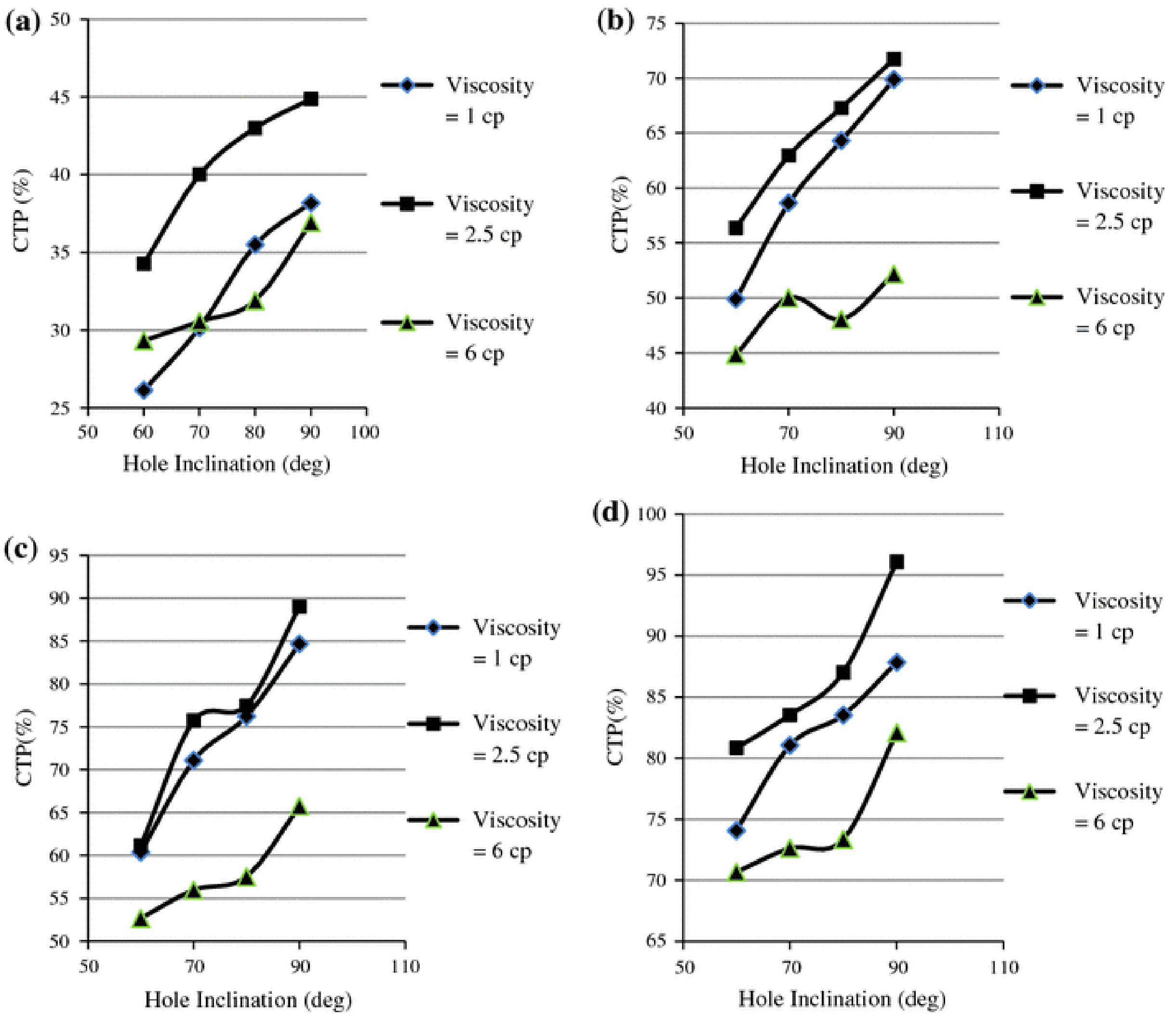


Figure 18—Cutting transport performance of vs hole inclinations for varied fluid viscosities (1, 2.5, 6 cp) and various distinct fluid velocities: a) V = 1.84 ft/s, b) = 2.21 ft/s, c) = 2.58 ft/s, and d) = 3.31 ft/s) (Piroozian et al. 2012).

Geometrical Definition and Modeling of Eccentric Annulus. Pipe-hole eccentricity is an indication of the degree of pipe off-centering within an open hole or another pipe. Usually, a percentage is used to express it. Most deviated, horizontal or even ER wells are in eccentric geometries which make the aspect of HC more problematic. For years, studies have been conducted to define and understand this term for better HC while directional drilling (Saad et al. 2024).

Lamb (1945) derived one of the earliest equations which relates flow rate and frictional pressure drop for laminar steady-state flow of Newtonian fluids in a concentric annulus as in Eq. 3,

$$Q = \frac{\pi}{8\mu}\frac{\Delta P_f}{\Delta L}\left[r_o^4 - r_i^4 - \frac{\left(r_o^2 - r_i^2\right)^2}{ln(s)}\right] \text{ , } \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

where Q is the flow rate in (gpm), μ is the viscosity in (cp), $\frac{\Delta P_f}{\Delta L}$ is the frictional pressure loss gradient in (psi/ft), r_i is the radius of inner pipe in (in), r_o is the radius of outer pipe in (in) and s is the pipe radius ratio of $\left(\frac{r_i}{r_o}\right)$.

Fredrickson and Bird (1958) examined non-Newtonian fluids, namely Bingham plastic and power law fluid models in concentric annulus. Inclusively, their findings resulted in a relationship between flow rate and frictional pressure gradient which is reported graphically.

Later, Bourgoyne (1986) developed an analytical solution for a slot flow approximation for a concentric annulus. It was stated that his assumption was thought to be quite accurate only for $\left(\frac{r_i}{r_o}\right) > 0.3$. According to Bingham plastic and power law fluids, the developed flow rate was as follows (**Eq. 4**),

$$Q = \frac{\pi r_o^4}{6\mu_p}\frac{\Delta P_f}{\Delta L}(1-s)^3\left[1-\frac{3}{2}\left(\frac{\tau_o}{1-s}\right)+\frac{1}{2}\frac{(\tau_o)^3}{1-s}\right], \tag{4}$$

where τ_o is the yield stress in (lbf/100ft^2), μ_p is the plastic viscosity in (cp).

Tao and Donovan (1955) theoretically studied the movement of Newtonian fluids in an eccentric annulus. Numerous assumptions are used in the theoretical portion of their work, some of which resulted in inaccurate flow rate estimation. The mathematical expression used to define the slot height (h), developed by them is as follows,

$$h = (r_o - r_i)(1 + e\cos\theta), \tag{5}$$

where e is the eccentricity and θ is the inclination angle.

In Eq. 5, Tao and Donovan (1955) assumed that the radial clearance $(r_o - r_i)$, and e are significantly small with limited values and assumes that the shear stress is in one dimension only. They supposed that when this term is represented in cartesian coordinates, they would be in the form of **Eqs. 6** and **7** for concentric annulus and eccentric annulus, respectively.

$$\frac{\partial \tau_{yz}}{\partial y} = \frac{\Delta P_f}{\Delta L}, \tag{6}$$

$$\frac{\partial \tau_{xl}}{\partial x} + \frac{\partial \tau_{yl}}{\partial y} = \frac{\Delta P_f}{\Delta L}, \tag{7}$$

Heyda (1959) described a method for calculating velocity profiles for Newtonian fluids in the most ideal coordinate system (eccentric annulus bipolar coordinates) to represent eccentric annular geometry assuming **Eq. 8** as,

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} = \frac{\Delta P_f}{\Delta L}, \tag{8}$$

Later, Iyoho and Azar (1981) avoided (Vaughn, 1965) simplified assumptions and published an analytical solution of power law fluid flow in an eccentric annulus six years after (Guckes, 1975). They changed the incorrect variant of the adjustable slot height which was adopted by (Tao and Donovan ,1955) and (Vaughn, 1965). However, in high velocities, their equation resulted in higher error in some cases. Iyoho and Azar (1981) utilized a bipolar coordinate system of two orthogonal circles to represent the eccentric annular geometry as in **Figure 19**. They derived the local annular clearance $h^*(\theta)$ between the drill pipe and the hole as (**Eq. 9**),

$$h^*(\theta) = \left(R_o{}^2 - e^2 sin^2(\theta)\right)^{0.5} - R_i + e\cos(\theta), \tag{9}$$

where R_o is the outer radius of drill pipe, R_i denotes the inner radius of outer pipe or hole, and e is the offset between the centers of drill pipe and the hole defined by Iyoho and Azar (1981) as **Eq. 10**,

$$e = R_o - R_i, \tag{10}$$

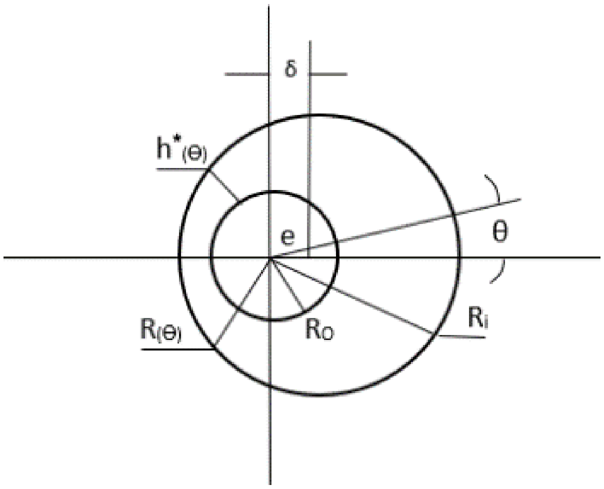


Figure 19—Geometric annulus definition in bipolar coordinates (Iyoho and Azar 1981).

Slot flow approximation was used in two recent studies by Luo and Peden (1987) and Uner et al. (1989). The inclination sections of 0º -10º, 10º-30º, 30º-60º, and 60º-90º were identified by Zamora and Hanson (1991) and the zones between 30º-60º are those where cleaning is the most challenging where cuttings bed slipping and cuttings settling are mostly encountered. The experimental findings of Saintpere and Marcillat's study (2000) supported the fact that when the angle is between 30º and 60º, there is a greater chance for pipe sticking while drilling.

As briefed earlier, the displacement of drill pipe from center of the wellbore is known as pipe hole eccentricity, and the flow regime of the drilling fluid determines how it affects HC. Walker and Li (2000) developed mathematical formulations of pipe eccentricity for laminar and turbulent flow as (**Eqs. 11** and **12**),

$$E_{lam} = 1 - 0.072\frac{e}{n}\left(\frac{d_b}{d_h}\right)^{0.8454} - \frac{3}{2}\, e^{2\sqrt{n}}\left(\frac{d_b}{d_h}\right)^{0.1852} + 0.96\, e^{3\sqrt{n}}\left(\frac{d_b}{d_h}\right)^{0.2527}, \ldots\ldots (11)$$

$$E_{turb} = 1 - 0.048\frac{e}{n}\left(\frac{d_b}{d_h}\right)^{0.8454} - \frac{2}{3}\, e^{2\sqrt{n}}\left(\frac{d_b}{d_h}\right)^{0.1852} + 0.285\, e^{3\sqrt{n}}\left(\frac{d_b}{d_h}\right)^{0.2527}, \ldots\ldots (12)$$

where E_{lam} and E_{turb} are pipe eccentricities for laminar and turbulent flow regimes, d_h and d_b are the wellbore and drill pipe diameters in (in), respectively.

Low wellbore inclinations (0º-55º) have negligible effects on HC from pipe eccentricity. Nonetheless, the impact increases in significance at high wellbore inclinations (55º-90º). Cuttings are less likely to be transported by the fluid because of the decreased fluid velocity and increased likelihood of a laminar flow regime. Due to this displacement, drilling fluid may flow preferentially along one side of the wellbore and accumulated cuttings on the other side leading to lower chances of instability and poor HC (Ramsey 2019; Kerunwa et al. 2021; Al-Shargabi et al. 2024). Typically, it is expressed as a percentage. If a pipe rests on the inside diameter of the surrounding pipe or hole, it will be considered 100 % eccentric. If it is perfectly centered within the outside circumference, it is 0 % eccentric.

HC Efficiency Assessment Using AI/ML, CFD Simulation, and Experimental Models. Lab and field experimental studies may have the capability to evaluate HC performance and fulfill optimization and prediction objectives. As well as numerical and intelligent studies, they may be utilized to simulate fluid flow and predict complex HC indicators for the optimization of deviated and horizontal drilling operations (Al-Rubaii et al. 2023). Thus, this section reviews the significance of using intelligent AI/ML, numerical-CFD and experimental models for efficient and real-time evaluation of HC conditions in deviated and horizontal drilling operations.

HC Assessment using real time AI/ML. The increasing acceptance of various AI/ML techniques in the industry of oil and gas is noteworthy (Ragab et al. 2021; Yakoot et al. 2021; Gomaa et al. 2021; Abdelbasset et al. 2022; Salem et al. 2022a and 2022b; Yehia et al. 2022; Gasser et al. 2021 and 2023). It can do multi-parameter optimization with dependable robustness (Rahmanifard and Plaksina 2019). Ozbayoglu et al. (2002) developed a feed forward neural network with back-propagation learning algorithm (BPNN) to investigate the cutting bed height in deviated and horizontal wells. In their study, they used Reynolds number (Re), Froude number (NFr) and CA as input parameters, whereas the cutting bed height was the output parameter. These dimensionless numbers are functions of inclination angle, feed cutting concentration, fluid density, fluid viscosity, average velocity, pipes dimensions and the wellbore. Rooki et al. (2014) and Rooki and Rakhshkhorshid (2017) used the BPNN and the radial basis neural networks (RBFN) for HC state indicating in foam drilling. In both studies, the authors used experimental data containing foam quality, foam velocity, eccentricity, RPM and subsurface conditions such as pressure and temperature as input parameters, whereas the cutting concentration was the output parameter. Al-Azani et al. (2018) concluded that support vector machine (SVM) can be used to predict the cutting concentration in the wellbore with higher accuracy. Holt and Ruel (2022) developed CleanSight®-a computer vision camera-mounted in rigs to evaluate the shaker load estimate (SLE) which is a measure of cuttings load on shale shakers (**Figure 20**). The AI workload is managed on the rig site by their developed camera, which combines high-resolution optical cameras with embedded edge computing capability. Using their cameras as a sensor, the images could be preprocessed by considering their sizes and scales them to fit the dimensions of the deep neural network (DNN), and a deep-learning technique for computer vision applications utilizing convolution neural network (CNN). The employment of computer vision cameras, CNN, and DNN applications resulted in continuous generation of SLE profiles that include images of cuttings on shale shakers. Their approach enabled them to assess cuttings accumulation in real-time drilling operations.

Figure 20—The developed optical CleanSight® rig site camera (Holt and Ruel 2022).

Awojinrin (2022) implemented a few ML algorithms such as: random forest regression (RFR), gradient boost regression, adaptive boosting (AdaBoost), stacking regression which are available as open-source packages in python to consider the rheology of the drilling fluid, geometrical aspects and drilling operation parameters when developing an AI workflow for estimating CA to evaluate hole-cleaning conditions. He used a heatmap to find the correlation matrix between drilling parameters, CA, and drilling fluid (**Figure 21**). A novel prediction framework based on hybrid machine-learning models was created and validated by (Davoodi et al. 2023). They calculated the flow velocity, PV, and YP of several WBM used in real oil and gas fields and resulted in an intelligent prediction framework with low prediction errors in the purpose of applying drilling fluids with more appropriate rheology for sufficient HC cleaning capabilities.

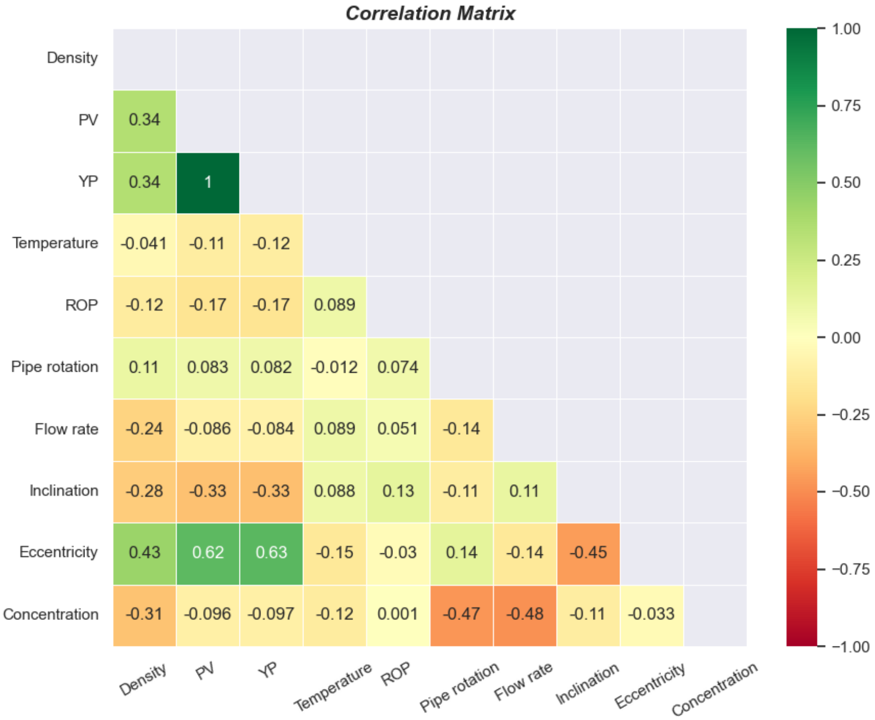


Figure 21—Correlation heat map for assessing the degree of correlation between drilling fluid, geometrical and drilling operation parameters and CA as an objective (Awojinrin 2022).

Most previous HC prediction models did not include the diagnostic tools required to assess cutting transportation and HC efficiency by combining AI/ML regression or pattern recognition (PR) algorithm in one single generalized framework. Hence, alternative techniques are needed to overcome these shortcomings and develop more generalizable cutting transport and HC models. **Table 4** presents a summarized literature of intelligent models for predicting cuttings transport efficiency. It is evident that there is still quite a bit of prospective advancements and progress in the field of HC recognition and intelligent modelling.

HC Assessment Using CFD Simulation. CFD approach has been frequently used to ascertain how cuttings are carried in the annulus (Bicalho et al. 2016; Heydari at al., 2017; Yan et al. 2020). One benefit of this approach is that it can yield comprehensive explanations of the intended characteristics without restricting layer models or experimental settings (Zhang et al. 2020). The CFD approach has been widely used to analyze variables including fluid velocity, rheological properties, ROP, drill pipe rotational effect, etc. (Zhu et al. 2023). Bilgesu et al. (2002) implemented one of the early CFD analyses done to comprehend cuttings transport process. They used particle-liquid multiphase flow model to analyze the effects of particle size and mud rheology on cuttings removal effectiveness. In horizontal and vertical flow geometries, water and a fluid with a non-Newtonian power law were both employed. The outcomes of the simulations demonstrated that annular velocity is significant to the wellbore HC. The impacts of fluid velocity, cuttings size, drill pipe rotation, and inclination angle in deviated wells were examined using the Eulerian model in a later work by Bilgesu et al. (2007) who utilized steady state CFD simulations. They revealed that the power law model outperforms the Herschel-Bulkley model using foam as a circulating drilling fluid for cuttings transportation. Also, the CFD simulation provides better cutting removal by increasing drill pipe rotation. Accordingly, studies (Rooki et al. 2014; Rooki et al. 2015) investigated the impact of drill pipe rotation, foam quality, foam velocity, wellbore inclination, and cuttings transport efficiency and concluded that increasing foam quality and pipe rotation improve cuttings removal. In both studies, the cuttings transport ratio (CTR), which is the ratio of annular solids velocity to fluid axial velocity, was used to analyze the cuttings transport efficiency.

Table 4—Summarization of AI/ML literature work for predicting HC efficiency.

Authors	Objective	Studied Parameters	Application
(Ozbayoglu et al. 2002)	Estimating the height of stationary cuttings beds deposited in horizontal and highly inclined wellbore.	Pump rates, fluid density and viscosity, ROP, wellbore geometry.	ANN
(Ulker and Sorgun 2016)	Estimation of cuttings transport in horizontal and deviated wells.	ROP, flow velocity, inclination angle, pipe rotation.	ANN, SVM, and K-nearest neighbors (KNN)
(Rooki and Rakhshkhorshid 2017)	Prediction of cutting concentration in underbalanced drilling.	ROP, flow velocity, inclination angle, pipe rotation.	ANN, RBFN
(Al-Azani et al. 2018)	Using support vector machine (SVM) technique to measure the HC efficiency in horizontal drilling.	Eccentricity, ROP, flow rate, inclination angle, pipe rotation, annulus size, temperature.	SVM
(Awojinrin 2022)	Modeling cuttings concentration using experimental data utilizing several machine learning (ML) techniques.	Fluid density, YP, PV, flow rate, temperature, inclination angle, hole eccentricity, pipe rotation, ROP.	Random forest, gradient boosting, adaptive boosting, stacked regression model
(Chowdhury and Hovda 2022)	Estimation of downhole cuttings concentration.	Annulus size, eccentricity inclination angle, ROP, cuttings density, temperature, fluid density, apparent viscosity, cuttings size, flow rate, pipe rotation.	Fuzzy logic models (FL)
(Han et al. 2022)	Predicting cuttings bed height in the well bore.	flow rate, cuttings size, ROP, eccentricity, wellbore diameter.	ANN, SVM, Long Short-Term Memory (LSTM) and recurrent neural network (RNN)
(Mendez et al. 2023)	Developing a data-driven model for predicting HC in deviated drilling.	Bit type, bit drilling time, pipe rotation, weight on bit, torque, formation type, rock properties, hydraulics, drilling mud properties.	Random Forest, Linear Regression, Neural Networks, Multivariate Adaptive Regression Spline, Support Vector Machine, and Boosted Decision Tree

Cuttings transport in extended reach wells under the influence of drill pipe rotation was studied by Wang et al. (2009). According to their CFD calculations, the drill pipe rotation might induce an unequal deposition of cuttings in the annulus. Also, Sorgun (2010) developed experimental and CFD models to investigate the cuttings transport phenomenon. Drill pipe rotation has been found to enhance cuttings removal and reduce the critical fluid velocity necessary to suspend particles in the flow stream. Further, Dewangan and Sinha (2016) used a computational multiphase flow strategy that took into consideration drilling fluid velocity and drill pipe rotational speed to estimate the distribution of cuttings at various radial distances from the center of a wellbore. This technique used the CFD Eulerian methodology. Their findings showed that cuttings accumulation in different pipe hole eccentricity degrees are greatly dependent on annular drilling fluid velocity and the rotational speed of the drill pipe (**Figure 22**).

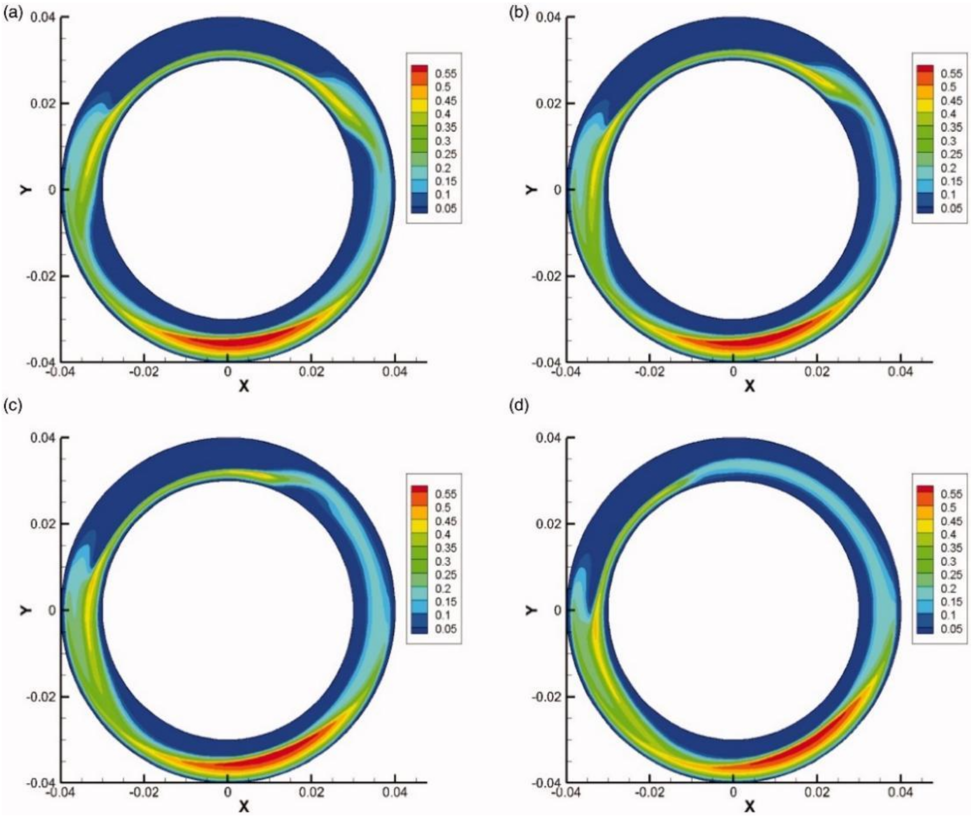


Figure 22—The impact of changing the inner cylinder rotating speed on the cross-sectional CA at the outlet for following inner cylinder rotational speed: (a) for 50 rpm, (b) for 100 rpm, (c) for 200 rpm, and (d) for 250 rpm (Dewangan and Sinha, 2016).

The majority of CFD models do not consider the interactions between the cuttings and the wellbore wall, the drill pipe, or the cuttings particles (Al-Shargabi et al. 2024). To solve these issues and provide more accurate cuttings deposition models, alternative techniques are recommended. Akhshik et al. (2016) simulated the impacts of cutting shape by implementing integrated CFD and the discrete element method (DEM) numerical model. The model considered the interactions between drilling fluid and cuttings, drill pipe rotation, drilling fluid density, and non-Newtonian rheological properties. Their work concluded that HC efficiency declines with increasing wellbore inclination and then improves as the wellbore gets horizontal. Pereira et al. (2007) investigated single-phase non-Newtonian fluid flow in an annulus. Their research indicated the viability of the chosen simulation methodology in reproducing experimental velocity profile data. In addition, they used the discrete phase model (DPM) to analyze multiphase particle-liquid flow phenomena in an annulus, paying close attention to particle trajectories as a function of drill pipe rotation. Although their model had good agreement with actual data, their approach did not consider several drilling variables. (Yilmaz, 2012) research entailed the development of a CFD model to examine cuttings bed height and velocities in deviated wellbores by utilizing DPM simulations for tracking of particle flow in the annulus. Given the low volume fractions involved, it was discovered that the one-way Lagrangian-Eulerian (LE) coupling scheme developed by Yilmaz (2012), was adequately representable to the transport phenomena of liquid and solid phases.

Demiralp. (2014) concentrated on how drill pipe whirling motion affected the efficiency of cuttings transport in eccentric horizontal annuli. His research involved the two-way coupling of particle-fluid interactions using the discrete element method (DEM), and as a result, he found that pressure increased in step with the whirling speed. Zhang et al. (2022) conducted multiphase flow simulation to study the effects of cuttings flow behavior on drilling tool surface conditions as indicated by the specularity coefficient (∅) which is an empirical parameter determined by the roughness of the material surface. They concluded in their findings that large cuttings or high (∅) coefficients can have an impact on how cuttings go through the central flow passage and may reduce the flow of small-sized cuttings or cause some energy losses (**Figure 23)**. Further, they demonstrated that both cutting accumulation and ineffective transportation can be caused by a low input air volume flow rate in the annulus.

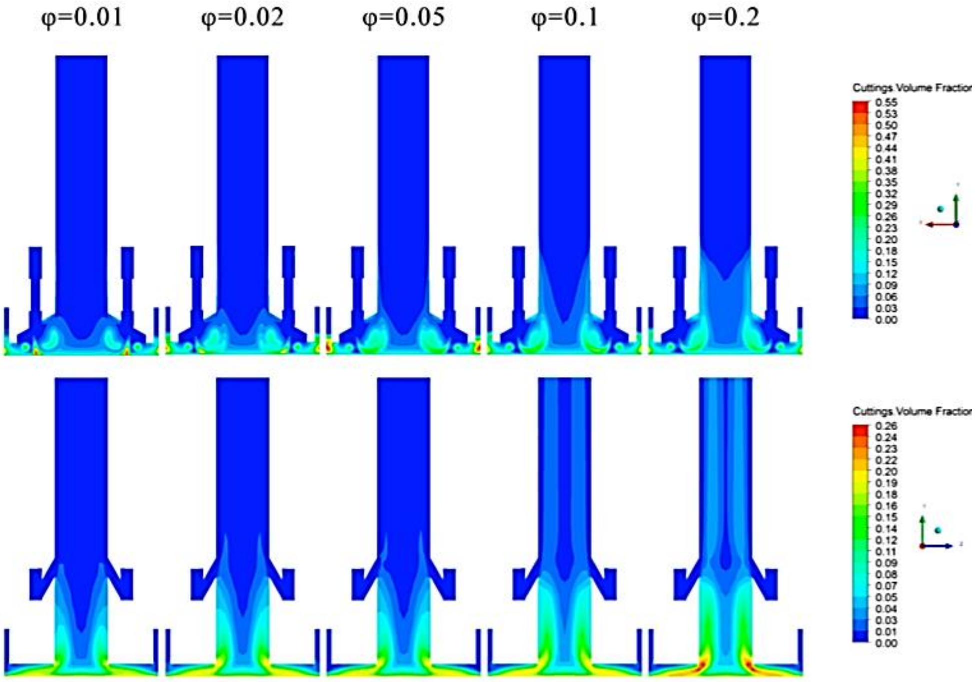


Figure 23—Volume fraction contour plots displaying the effect of specularity coefficient (ϕ) on cutting particle distribution (Zhang et al. 2022).

To explore the cuttings movement during back reaming operation, a new method using a Eulerian-Granular approach was proposed by Zhu et al. (2023) utilizing the linked layering-sliding mesh method (**Figure 24)**. While the sliding mesh model represents the rotation of the pipe, the dynamic layering approach is used to simulate the axial movement of the pipe. They concluded that CA will significantly rise because of increasing the connector diameter (**Figure 25**). They stated that cuttings are built up around the connector due to two major causes: the connector pushing action, which resembles a "bulldozer," and the variation in cross-sectional area. Accordingly, their findings revealed that CA may rise with increasing length, slope, and initial bed height. In addition, CA decreases with a large increase in pipe rotational speed.

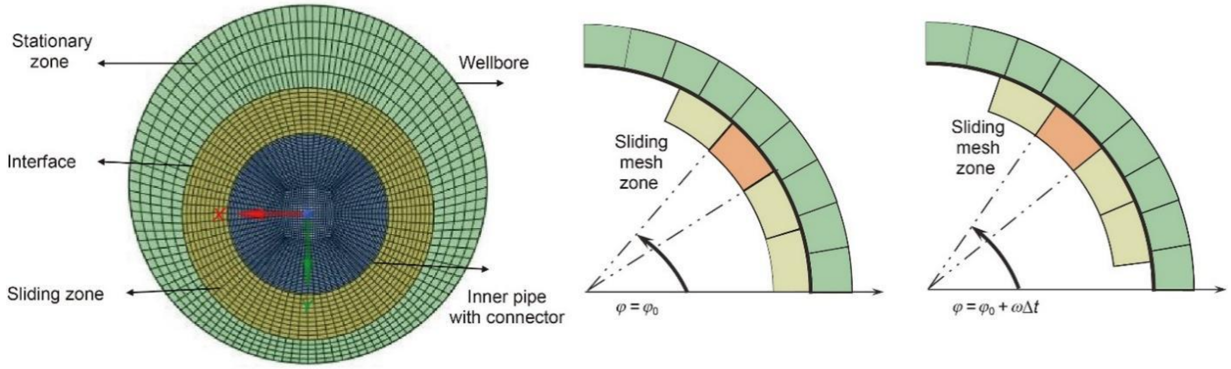


Figure 24—Schematic representation of linked layering-sliding mesh method (Zhu et al. 2023).

Towards the end, the following are drawbacks of using CFD numerical simulations: 1) mistakes might arise from oversimplified boundary conditions or flow models; 2) potential uncertainties brought on by calculating values per cell being insufficient, which might lead to interpolation mistakes. To guarantee correctness, CFD simulations should be verified against experimental or field physical data to evaluate HC conditions in deviated and horizontal wellbores.

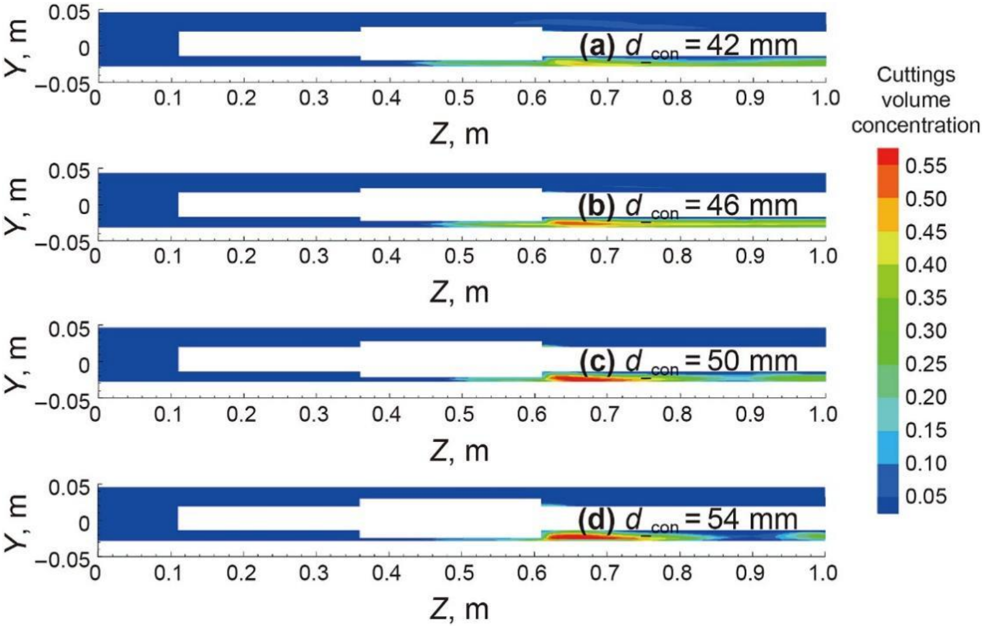


Figure 25—Contours of the cuttings volume concentration under various connector sizes (Zhu et al. 2023).

HC Assessment Through laboratory and Field Experimental Studies. Several experimental investigations have been carried out to optimize the effectiveness of HC during drilling operations, which is essential for preserving the wellbore integrity and guaranteeing safe and effective drilling operations.

To assess the impact of the orbital motion of an inner tube on the eccentric annulus, Bicalho et al. (2016) conducted an experimental evaluation of the laminar and isothermal helical flow of non-Newtonian fluids into horizontal annular sections with partial obstruction (**Figure 26**). Based on the experimental results, four variables were found to be significant for the annular flows. The most important one was fluid rheology, which was followed by fluid flow rate, both of which contributed to the increase in pressure drop. Also, eccentricity was found to have had the opposite effect. Moreover. The impact of inner tube rotation on the pressure drop was minimal under the examined flow conditions. **Table 5** displays the values of independent variables for experimental work (Bicalho et al. 2016).

Figure 26—Flow loop apparatus for cuttings transportation experimental study (Bicalho et al.2016).

Table 5—Independent variables investigated in experimental design (Bicalho et al. 2016).

Apparatus level	Xanthan gum (XG) concentration (% by mass)	Eccentricity	Flow rate (ft3/min)	Pipe rotation (rpm)
-1	0.1	0	1.8	0
0	0.3	0.23	3.5	200
1	0.5	0.46	5.3	400

A complete horizontal cuttings transport flow loop was set up and 136 trials were carried out by Song et al. (2017). The effects of flow rate (0.00058-0.00078 m^3/s), cuttings diameter (0.0003-0.005 m), rate of ROP (0.415-1.25 ft/min), eccentricity (0-0.8), and wellbore diameters (1.57-3.15 in) on HC were determined by analyzing the volumetric concentration of cuttings and the dimensionless height of the cuttings bed. It was discovered that by increasing cuttings diameter, HC efficiency first increased and then declined. The primary variable was the flow rate. They concluded that in micro-hole horizontal wells, increased flow rate, lower ROP, lower eccentricity, and a smaller drill pipe/wellbore diameter ratio all contributed to improved HC efficiency. Later, Song et al. (2024) investigated the friction between the drill pipe and the cuttings bed was investigated through laboratory tests (**Figure 27**). Their experimental work examined the impact of drill pipe rotation speed, cuttings size, depth, and fluid viscosity on the overall sliding-friction coefficient (CSFC). They indicated that the greater the difference between the cuttings size and the critical cuttings size, the more fluid viscosity will affect the CSFC. Further, smaller cuttings size than the critical ones will lead to gradual decrease in CSFC will gradually and eventually to cutting stabilization. **Table 6** shows the parameters tested in 135 experimental trials carried out by Song et al. (2024).

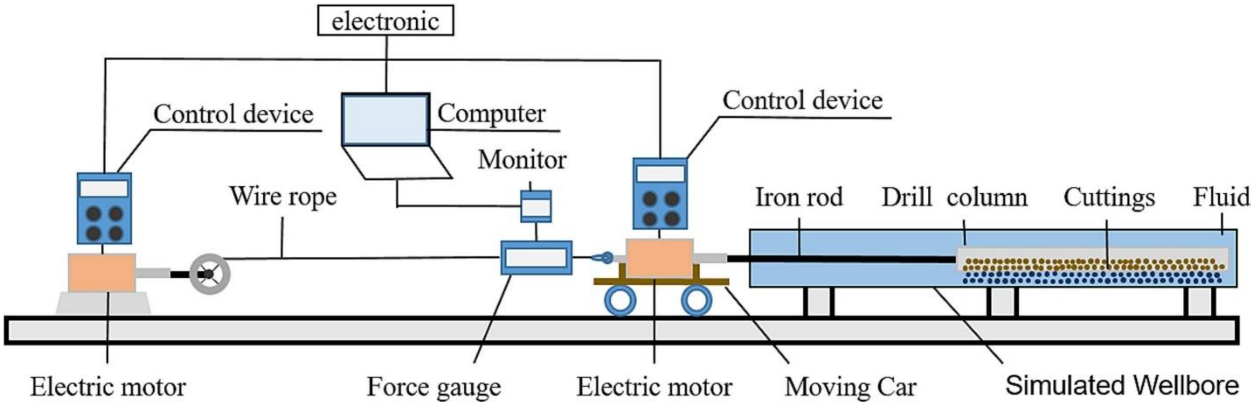


Figure 27—A schematic of the experimental setup (Song et al.2024).

Table 6—Parameters investigated in (Song et al. 2024) experimental design.

Dimensionless depth	Average cuttings size (in)	Pipe rotation (RPM)	Drilling fluid viscosity (cp)
0, 0.2, 0.4	0.05, 0.09	0, 5, 7, 10, 15	1, 2.4, 5.94, 8.92
0.6, 0.8, 1	0.01	20, 30, 40, 50	12.46, 23.59

In summary, experiments may be used to examine the effects of various factors on HC. However, it can be ascertained that the existing deficiencies in this line of experimental investigations are caused by variances in wellbore geometry, solid properties, flow parameters, etc., which lead to difficulties in the execution of testing under most flow down hole environments (Pang et al. 2019; Saad et al. 2024). When thinking about the effects of drilling and HC, these difficulties are typically perceived when the flow and drilling rate are experimentally combined for experimental investigation (Song et al. 2017).

Summary and Conclusions

This paper comprehensively reviews cuttings transport in deviated and horizontal eccentric wells to fill the gaps in the knowledge of hole cleaning (HC) efficiency and ensure successful directional drilling operations. Based on that, the following conclusions can be drawn:

1. HC indicators – transport ratio (V_{TR}), carrying capacity index (CCI), and equivalent circulating density (ECD) – are the most influential aspects on HC in eccentric wells.
2. At zenith angles between 0° and 30°, cuttings are effectively carried by mud flow at notably higher velocities. Cutting deposition occurs at zenith angles greater than 30°.
3. In the turbulent flow regimes, deposited cuttings rise in the form of dunes on the cuttings/drilling fluid contact surface and at lower velocities, they mix upward as a single mass.
4. For both turbulent and laminar flows at inclination angle ranges of (0°-55°), pipe eccentricity has no effect on HC. In contrast, the impact will be more noticeable at higher inclinations (55°-90°).
5. Inner pipe rotation significantly improves the stationary bed height in the annulus. However, no significant improvement is observed for rotations above the range of (80-120) rpm.
6. Deviated annuli experiences more uniform flow distributions with inner drill pipe rotation, which maintains low stagnating flow of cuttings.

7. Drill pipe entrapment issues can be avoided, and cuttings transport can be enhanced in the event of a partly blocked with highly eccentric annulus by increasing drill pipe rotation.
8. The transportation of cuttings in deviated and horizontal wellbores while drilling unconventional shale formations which are characterized by nano-sized pores, can be enhanced by nanoparticles through colloidal interactions.
9. The foam ability to move cuttings is dependent on the drilling fluid stability and rheology. Accordingly, in horizontal wells, unstable foams lead to phase separation and the formation of a gas/liquid flow pattern.
10. The velocity and quality of foams are strongly dependent on temperature and pressure, making them the primary parameters influencing foam-based sweeps.
11. Thick cuttings dunes are not always the result of increased tripping velocity. Instead, the accumulation of cuttings surrounding the connection is primarily caused by two factors: the push-like impact of the connector and variations in cross-sectional area.
12. The "bulldozer" impact of the drill pipe connections is stronger when the tripping velocity is higher than the cuttings. On the other hand, the primary cause of cuttings accumulation is the influence of the difference cross-sectional area. This connector/bulldozer action has a greater negative effect on HC.
13. Because of the high pressure and temperature during high pressure high temperature (HPHT) drilling, cuttings may stick to the wellbore walls and have a substantial influence on HC, drilling efficiency or even increased equipment wear rate. In order overcome these issues, operators frequently employ high-viscous drilling fluid that has an optimal range of bentonite (pH adjuster) to control sweeping efficiency to enhance HC and keep cuttings from sticking to the wellbore walls.
14. Most CFD Analyses indicate that in deviated and horizontal annuli, turbulent flow regime improves HC without forming a fixed cutting bed. Moreover, in transitional flow, a moving bed is combined with a stationary bed, while in laminar flow, the bed is fully stationary in the annular region. More noteworthy, the more the specularity coefficient ($\emptyset$) values, the greater the momentum loss of the cuttings.

Recommendations for Future Potential and Further Studies. To help understand HC in horizontal and deviated wells, this review provides the following guiding principles for further research:

1. Enhancing drilling fluid performance, raising the annulus fluid velocity, speeding up the rotation of drill pipe, and mechanical cuttings removal operations are some of the common techniques for removing cutting beds. However, these techniques have drawbacks as well. Hence, enhancing drilling fluid performance may increase costs, while over rotating the drill bit may cause tool malfunction. To mitigate the issues, it is recommended to enhance the ability to remove cuttings by upgrading the drill string utilizing innovative cuttings removal assemblies.
2. There is a little variation in the cumulative cuttings bed height under various tripping velocities due to "bulldozer" effect of the drill pipe connections leading to severe impact on HC. For this reason, it is recommended that during the back reaming operations, the tripping velocity to be slower than the sand velocity.
3. For inclinations up to 62º, it is recommended using HC indicators (V_{TR}, CCI, and ECD) in eccentric wellbore geometries in proposed ranges (13-15 lb/gal, 0.5-1, and 0.8-1), for the different eccentricity values (0, 0.4 and 0.8), respectively.
4. The action mechanism of different cuttings removal down hole equipment and BHAs may be better understood by using further CFD numerical simulations. This may be useful for local HC while drilling deviated and horizontal wells.
5. The cuttings removal impact of different tools may be more accurately assessed using CFD numerical simulations. Additionally, the changing law of the cuttings volume fraction due to density of cuttings, can be determined based on the cuttings multiphase flow models.

6. In a fine wellbore wall condition, such a cased well, cuttings are more easily conveyed to the surface than in an open wellbore wall. Thus, it will become recommended to implement further studies on how to guarantee lower values of specularity coefficient ($\emptyset$) regarding deviated and horizontal wellbores.
7. Yet, there are number of shortcomings exist in the models used to assess drilling performance and HC directional and eccentric wells. These include the failure to consider eccentricity factor, cutting characteristics, flow regime and the sweeping efficiency and rheological features of drilling fluids. Directional drilling techniques may be greatly impacted by these variables. Resolving these issues may increase HC assessment accuracy, dependability, boosting drilling efficiency and safety.

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Nomenclature

$(r_o - r_i)$ = Radial Clearance
ρ_f = Drilling Fluid Density
$\frac{\Delta P_f}{\Delta L}$ = Frictional Pressure Loss Gradient
d_h = Wellbore Diameter
d_p = Drill Pipe Diameter
r_i = Inner Radius of Stationary Pipe
r_o = Outer Radius of Inner Pipe
μ_p = Plastic Viscosity
τ_o = Yield Stress
$\emptyset$ = Specularity Coefficient
AI = Artificial Intelligence
ANN = Artificial Neural Network
BHA = Bottom Hole Assembly
CA = Cuttings Concentration
CCI = Carrying Capacity Index
CFD = Computational Fluid Dynamics
CNCs = Cellulose Nanocrystals
CNPs = Cellulose Nanoparticles
CTP = Cutting Transport Performance
DEM = Discrete Element Method
DPM = Discrete Phase Model
ECD = Equivalent Circulating Density
ERD = Extended Reach Drilling

ESD = Equivalent Static Density
G = Hole Angle Factor
h = Slot Height
HC = Hole Cleaning
HPHT = High Pressure High Temperature
K = Consistency Index Factor
LCM = Lost Circulation Material
LE = Lagrangian-Eulerian
ML = Machine Learning
OBM = Oil-Based Mud
PR = Pattern Recognition
PV = Plastic Viscosity
Q = Flow Rate
ROP = Rate of Penetration
Rp = Reynold's Number of Terminal Settled Particle
RPM = Drill string rotation
RSDS = Rotary Steerable Drive System
RSS = Rotary Steerable System
Va = Annular Velocity
V_S = Slip Velocity
V_T = Cuttings Transport Velocity
WBM = Water-Based Mud
WOB = Weight on Bit
XG = Xanthan gum
YP = Yield Point
e = Offset Between Centers of Two Pipes

Conflict of interest

The author(s) declare that they have no conflicting interests.

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