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Modeling and Optimization of Hole Cleaning in Extended Reach Wells: Integrated Rheological and Operational Analysis Using WELLPLAN

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Abstract: *Efficient hole cleaning remains one of the most critical operational challenges in highly deviated and extended reach wells, where conventional gravitational cuttings transport is severely compromised. This study presents a comprehensive investigation of the hydromechanical and rheological factors influencing cuttings transport, bed formation, and suspension efficiency in deviated wellbores. The research integrates analytical, numerical, and simulation-based approaches, leveraging advanced drilling hydraulics modeling in WELLPLAN to quantify the impact of drilling fluid properties, well trajectory, and operational parameters on hole cleaning performance. Specifically, the study examines the roles of drilling fluid rheology including plastic viscosity, yield point, gel strength, and density on the suspension and transport of solids under varying annular flow conditions, flow regimes, and well inclinations. Operational variables, such as drill pipe rotation, flow rate modulation, rate of penetration (ROP), and circulation interruptions, were systematically evaluated to assess their influence on cuttings mobilization, erosion time, and critical velocity thresholds. Simulation results reveal that optimal hole cleaning is achieved through a synergistic combination of moderate plastic viscosity, appropriately weighted mud, and flow rates sufficient to maintain turbulent or pseudo-turbulent regimes, particularly in horizontal sections exceeding 60° deviation. Excessively high viscosity or sub-critical annular velocities were identified as primary contributors to cuttings bed formation, increased torque and drag, and potential stuck pipe events. The study further establishes threshold operational parameters, including minimum annular velocities and mud weight windows, necessary to prevent bed accumulation while minimizing Equivalent Circulating Density (ECD) and formation fracturing risks. Sensitivity analyses highlight the relative importance of fluid rheology versus mechanical agitation (pipe rotation) in mitigating cuttings deposition across different deviated well geometries. This work provides a robust framework for the integrated design of drilling fluid systems and operational practices in complex wellbores, offering predictive insights for real-time drilling optimization and risk mitigation. The findings have direct implications for the planning and execution of extended reach drilling projects, particularly in mature petroleum provinces such as the Niger Delta, where wellbore stability and operational efficiency are constrained by challenging formation conditions and narrow drilling margins.*

Keywords— Hole cleaning; cuttings transport; deviated wells, drilling fluid rheology; annular flow; pipe rotation; equivalent circulating density; WELLPLAN simulation; operational optimization; extended reach drilling.

1. INTRODUCTION

The safe and efficient drilling of oil and gas wells critically depends on the intelligent design and management of drilling fluids. Commonly referred to as drilling muds, these fluids serve multiple essential functions: they provide hydrostatic pressure to counter formation fluids, cool and lubricate the drill bit, suspend and transport drill cuttings to the surface, and stabilize wellbore walls to prevent collapse or sloughing. Among these roles, efficient hole cleaning is particularly challenging in highly deviated or extended reach wells, where complex fluid dynamics can severely compromise cuttings transport [18].

Over the past four decades, the industry's shift toward directional, extended reach, and horizontal drilling has significantly increased the importance of optimizing drilling fluid properties for hole cleaning [11]. Deviated wells introduce unique mechanical and hydraulic complexities that fundamentally alter cuttings transport mechanisms compared to vertical wells. In vertical wells, gravitational settling aids cuttings transport; however, in wellbores inclined beyond 30 degrees and especially in horizontal sections of 60-90 degrees, gravity no longer dominates. Cuttings tend to accumulate along the low side of the annulus, increasing the risk of stuck pipe, elevated torque and drag, pack-offs, and potentially catastrophic wellbore failure [22].

Drilling fluid design for highly deviated wells must address complex flow regimes characterized by secondary patterns, such as spiral or helical flows, and navigate transitional and turbulent behaviors in non-uniform annular geometries [18]. The interplay between fluid rheology, annular velocity, cuttings size distribution, and wellbore inclination produces a highly non-linear system requiring detailed modeling and

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real-time control strategies [24]. Hole cleaning efficiency is primarily dictated by the fluid's ability to generate sufficient shear stress at the cuttings bed interface to lift and transport solids out of the annulus. Rheological properties including plastic viscosity, yield point, and gel strength must strike a balance between suspension capacity under static conditions and minimal pressure losses during circulation [6]. Excessively viscous fluids, while improving cuttings suspension, can raise equivalent circulating density (ECD) to levels that risk fracturing weak formations, whereas low-viscosity fluids may fail to lift cuttings, particularly at high inclinations where gravitational assistance is minimal [7].

Empirical and numerical studies consistently demonstrate that cuttings transport is highly sensitive to annular velocity profiles [8]. In horizontal sections, maintaining flow above a critical velocity is essential to prevent stationary cuttings beds, which increase drag, torque, and the likelihood of stuck pipe [17. While operational levers such as pipe rotation and pump rate remain key to mitigating cuttings accumulation, the inherent properties of the drilling fluid fundamentally govern their effectiveness [12]. Non-Newtonian fluids, particularly water-based and oil-based muds exhibiting yield stress behavior, demonstrate superior cuttings carrying capacity compared to Newtonian fluids in deviated well geometries [13]. Advanced rheology modifiers, polymers, and high-performance viscosifiers allow engineers to tailor fluid properties to specific hole cleaning challenges, often in combination with mechanical techniques such as drillstring rotation and optimized cleaning sweeps [11].

Despite advances in computational fluid dynamics (CFD), machine learning-based predictive models, and downhole measurement technologies, field operations still face practical constraints including formation characteristics, downhole temperatures and pressures, fluid contamination, and economic trade-offs between chemical additives and rig time [19], [22]. Real-time monitoring of hole cleaning performance remains reliant on indirect indicators such as torque and drag trends, flowline solids measurements, cuttings return quality, and downhole pressure readings, all of which are subject to measurement uncertainty [24]. In regions like the Niger Delta, where extended reach and highly deviated wells are increasingly common, these challenges are exacerbated by complex lithologies, unstable formations, and narrow operational margins, making optimized hole cleaning essential to minimize non-productive time, avoid stuck pipe, and preserve wellbore integrity [7].

In this study, the dynamics of cuttings transport and hole cleaning in deviated wells are investigated using numerical simulation techniques. The methodology involves evaluating the combined effects of drilling fluid rheology, mud weight, flowrate, and wellbore inclination on cuttings carrying efficiency, cuttings bed formation, and erosion time. Mathematical models incorporating key parameters such as plastic viscosity, yield point, fluid density, annular velocity, and wellbore geometry are implemented to simulate particle suspension and transport along deviated and horizontal well sections. The simulations are conducted using specialized drilling engineering software, such as WELLPLAN, which allows for detailed modeling of annular flow regimes, laminar–turbulent transitions, and cuttings bed behavior under varying operational conditions. Sensitivity analyses are performed to identify optimal ranges of fluid properties and hydraulic parameters required to sustain efficient cuttings transport while minimizing the risk of cuttings accumulation, stuck pipe, and excessive equivalent circulating density. This approach provides a quantitative framework for designing drilling fluid programs and optimizing operational parameters to enhance hole cleaning performance in complex wellbore geometries.

2. Hole Cleaning

2.1 Hole Cleaning Challenges in Highly Deviated Wells

The complexity of hole cleaning in highly deviated and horizontal wells represents a critical operational and economic challenge in modern directional drilling [22], [10]. Effective cuttings transport under non-vertical conditions requires a detailed understanding of the interactions among well trajectory, annular flow behavior, particle dynamics, drilling fluid rheology, and operational parameters such as flow rates and drill string rotation [1], [11]. As deviation angles increase, the role of gravity in assisting cuttings transport diminishes, and fluid drag forces become the dominant mechanism for mobilizing cuttings [12], [15]. In low to medium inclination angles, cuttings may slide along the low side of the wellbore, potentially forming stationary beds if the carrying capacity of the fluid is insufficient [6]. In extended reach and horizontal sections, flow regime control, velocity distribution, and turbulence intensification become critical to maintain a balance between deposition and resuspension, as any loss of momentum transfer can rapidly lead to severe bed accumulation, pack-offs, or stuck pipe incidents that compromise wellbore integrity and drill string operability [18],[13].

Cuttings bed formation in deviated wells is a dynamic process driven by the imbalance between deposition and erosion along the annulus [3], [17]. The development of stationary cuttings beds reduces the effective flow area, which further lowers annular velocities and promotes additional deposition in a positive feedback loop [24]. This phenomenon is highly sensitive to drilling fluid rheology, annular eccentricity, pipe placement, and transitions between laminar and turbulent flow regimes [8]. Non-Newtonian fluids must be designed with sufficient yield stress to suspend cuttings under static conditions while maintaining low enough resistance to allow efficient displacement during circulation [4], [9]. Inadequate rheological design increases the risk of stable cuttings beds, higher hydraulic pressure losses, and elevated torque-and-drag forces [11], [5].

Wellbore inclination and trajectory significantly influence hole cleaning efficiency. Empirical data and laboratory experiments demonstrate that transport efficiency declines sharply beyond 30 degrees deviation, with horizontal sections requiring higher annular velocities and mechanical agitation such as drill string rotation to maintain cuttings suspension [22], [2]. Sharp doglegs and abrupt changes in wellbore trajectory introduce additional complications by creating localized flow separation, secondary vortices, and turbulent eddies, which can either enhance or inhibit particle entrainment [29], [25]. Poorly planned trajectories can act as cuttings traps, necessitating operational interventions such as increased pump rates, wiper trips, or high-viscosity sweep treatments to prevent excessive bed buildup [21], [1].

The rheological properties of drilling fluids are critical in determining their suspension and carrying capacity. Plastic viscosity, yield point, and gel strength must be carefully balanced to suspend cuttings during static periods and maintain turbulent flow under circulation [7]. Excessively high yield stress increases equivalent circulating density (ECD) and formation fracture risk, while low gel strengths promote rapid cuttings drop-out [5], [13]. Shear-thinning fluids are desirable in deviated wellbores because they allow high downhole flow rates without excessive pressure losses, thereby improving cuttings transport efficiency [18]. Turbulent flow is particularly advantageous in horizontal sections, as it increases drag forces on particles and disrupts boundary layers where cuttings tend to accumulate, making Reynolds number control a key design objective [3], [28].

Mechanical agitation through drill string rotation has been shown to enhance hole cleaning by generating secondary flows that lift settled cuttings back into the main flow [4], [12]. Drill string eccentricity further modifies annular flow profiles, creating high-velocity regions on the narrow side and low-velocity zones on the wide side where cuttings may accumulate [5]. Optimizing string centralization, stabilizer placement, and rotational speed is therefore essential to counteract the asymmetric deposition tendencies and improve overall annular cleaning efficiency [20].

Hydraulic parameters including pump rate, annular velocity, hole diameter, and pipe-to-borehole ratios play a central role in cuttings transport [6], [23]. Minimum critical velocities must be maintained to prevent stationary bed formation, with recommended annular velocities in highly deviated sections often exceeding 3-4 ft/s depending on cuttings size and fluid properties [17]. Operational practices such as staged flowrate increases, periodic wiper trips, and high-viscosity sweep treatments are employed to augment hole cleaning, particularly in unconsolidated formations that generate high cuttings volumes [3], [18].

Modern drilling engineering increasingly relies on numerical modeling and simulation to predict and optimize hole cleaning performance [2]. Software platforms such as WELLPLAN integrate trajectory, fluid, and pipe data with operational parameters to simulate cuttings transport, annular flow regimes, torque and drag, and critical cleaning velocities for each well section [7], [20]. While these models provide valuable insights, limitations remain due to assumptions such as uniform cuttings size distribution, simplified annular eccentricity effects, and the neglect of real-time formation breakouts [13]. Continuous validation against field data is therefore essential to improve predictive accuracy in complex wellbores [18], [22].

Inefficient hole cleaning in highly deviated wells can have severe consequences, including increased torque and drag, stuck pipe, pack-offs, elevated ECD leading to formation fracturing, and overall wellbore instability [29], [4]. Poor cuttings transport prolongs drilling time, increases non-productive time, and drives up operational costs due to remedial interventions [10], [5]. In extreme cases, catastrophic stuck pipe events can lead to the loss of the bottom hole assembly and necessitate costly sidetracks or well abandonment, highlighting the operational imperative of robust hole cleaning strategies in modern directional drilling operations [25].

2.2 Drilling Fluid Parameters Affecting Hole Cleaning

The effective removal of drilled cuttings in highly deviated and horizontal wells is strongly governed by the selection, design, and optimization of drilling fluid properties [7]. Drilling fluids, or muds, perform multiple functions, but for hole cleaning, their capacity to suspend, transport, and re-suspend drilled solids under varying dynamic conditions is critical [2], [13]. Achieving efficient cuttings transport in deviated wellbores requires careful consideration of fluid type, rheological and physical properties, flow regime, chemical additives, and the influence of downhole temperature and pressure [9].

Drilling fluids are commonly classified based on their continuous phase into water-based muds (WBMs), oil-based muds (OBMs), and synthetic-based muds (SBMs) [16], [3]. WBMs are widely used due to their cost-effectiveness and environmental acceptability and typically rely on clay minerals and polymers to control rheology and filtration [1]. While WBMs provide satisfactory cuttings suspension under moderate conditions, their performance can deteriorate in reactive shale formations, where water influx and clay swelling generate additional fine solids that challenge hole cleaning efficiency [14]. OBMs, formulated with mineral oils, diesel, or synthetic hydrocarbons, offer superior lubricity, shale inhibition, and thermal stability, making them suitable for extended reach and HPHT wells [12], [26]. Their invert emulsion structure enhances cuttings carrying capacity, but environmental regulations and disposal requirements often restrict their use [31]. SBMs combine the advantages of OBMs with improved environmental performance and biodegradability, providing stable rheological behavior and suspension capabilities while meeting regulatory constraints [27], [4].

Fluid density, commonly expressed as mud weight, is a primary determinant of cuttings transport efficiency [5]. Adequate mud weight generates sufficient hydrostatic pressure to maintain wellbore stability and prevent influx, while also imparting buoyancy to cuttings, reducing their tendency to settle along the low side of highly deviated sections [8]. Higher mud density decreases cuttings slip velocity and enhances vertical transport; however, excessive mud weight increases equivalent circulating density (ECD), raising the risk of formation fracturing and lost circulation, which can adversely affect hole cleaning [9], [23].

Rheological parameters, including plastic viscosity (PV), yield point (YP), and gel strength, define the fluid's capacity to transport and suspend solids under both dynamic and static conditions [3]. PV represents flow resistance due to internal friction and is influenced by solids concentration and base fluid viscosity. While higher PV improves suspension at high shear rates, it increases pump pressure requirements and hydraulic horsepower [2]. YP reflects the fluid's ability to carry cuttings under laminar or low-velocity conditions, critical in inclined or horizontal well sections [4], [13]. Gel strength ensures cuttings remain suspended when circulation stops, but excessively high values can lead to surge and swab pressures during pipe movement [24]. Optimal combinations of PV, YP, and gel strength are therefore essential to maintain carrying capacity without compromising pumpability or inducing pressure fluctuations [5], [31].

The annular flow regime further governs cuttings transport efficiency (Mahmoud, Hamza, et al., 2020). Turbulent flow enhances particle drag and disrupts boundary layers near the borehole wall, minimizing the risk of cuttings bed formation [4], [13]. In highly deviated wells, achieving fully turbulent flow may be limited by surface equipment or pressure constraints; hence, drilling fluids are engineered to sustain adequate lift and carrying capacity even under transitional or pseudo-laminar flow conditions [7]. Mechanical interventions such as pipe rotation and reciprocation are often used in combination with fluid flow to mechanically re-suspend settled cuttings and improve overall hole cleaning [3], [11].

Chemical additives play a critical role in tailoring drilling fluid performance for cuttings transport [5], [27]. Viscosifiers such as bentonite and high-performance polymers increase low-shear viscosity and yield stress, enhancing carrying capacity [9]. Weighting agents, commonly barite or hematite, adjust fluid density to maintain hydrostatic pressure and improve buoyancy effects [2]. Shale inhibitors reduce clay swelling and fine solids generation, while thinners and dispersants control excessive viscosity and prevent flocculation [3], [16]. Fluid loss control agents minimize filtrate invasion and stabilize the borehole, preventing cuttings disintegration [4], [28]. The precise balance of these additives is necessary to avoid undesirable effects such as excessive gelation, emulsion destabilization, or rheological degradation [5], [30].

Downhole temperature and pressure conditions significantly affect drilling fluid behavior, particularly in extended reach and HPHT wells [26]. Elevated temperatures can degrade polymers, reduce base fluid viscosity, and destabilize emulsions, diminishing cuttings suspension [30]. Pressure variations influence fluid compressibility, gas solubility, and emulsion stability [4], [17]. Rheological properties measured at surface conditions may therefore be inadequate at bottomhole conditions, necessitating the use of HPHT rheometers to simulate downhole conditions and calibrate formulations [5]. Accounting for these effects ensures that drilling fluids maintain their designed suspension and transport capabilities throughout the wellbore trajectory, enabling efficient and safe hole cleaning in highly deviated environments [3], [28].

2.3 Well Operational Parameters Affecting Hole Cleaning

Well operational parameters exert a profound influence on cuttings transport efficiency, annular hydraulics, and overall hole cleaning performance, particularly in highly deviated and horizontal wells [2]. Among the most significant operational variables are pump rate, flow velocity, rotational speed of the drill string, pipe eccentricity, tripping and sliding practices, and the choice of bottomhole assembly (BHA) components [13]. Each parameter interacts dynamically with drilling fluid properties and wellbore geometry, resulting in highly nonlinear effects on cuttings transport, bed formation, and torque-and-drag response [4].

Pump rate and annular flow velocity are among the most critical factors affecting hole cleaning. Higher pump rates increase annular velocity, which enhances the shear forces acting on cuttings and reduces the tendency for bed formation along the low side of inclined wellbores [3], [23]. However, excessive pump rates can generate overbalanced pressures, elevate equivalent circulating density (ECD), induce formation fracturing, and increase erosion of the wellbore and BHA components [9]. Optimizing pump rate thus requires a careful balance between achieving sufficient hydraulic carrying capacity for cuttings and maintaining safe downhole pressure margins [5].

The rotational speed of the drill string also plays a critical role in enhancing cuttings transport. Drill string rotation generates secondary flow patterns, breaks up stationary cuttings beds, and redistributes particles into higher-velocity regions of the annulus [4], [11]. In combination with eccentric pipe placement, rotation produces asymmetric annular flow, which can either enhance or hinder particle entrainment depending on the wellbore geometry and fluid rheology [5], [29]. For horizontal and extended reach sections, maintaining optimal rotational speed is essential to prevent cuttings accumulation on the low side while minimizing torque-and-drag penalties [20].

Tripping operations, whether pulling out or running in the hole, significantly affect cuttings transport and suspension. During pipe movement, surge and swab effects alter effective bottomhole pressure and fluid velocity, impacting the stability of cuttings beds and potentially inducing pack-offs [3], [13]. Controlled tripping speeds and simultaneous adjustment of pump rates are necessary to mitigate adverse surge/swab effects and maintain continuous cuttings transport [2], [28]. Sliding operations, often required in directional drilling for trajectory control, present additional challenges because rotational energy is reduced or absent, diminishing secondary flow generation and increasing the risk of cuttings accumulation on the low side [4]. In such cases, increased annular velocity, intermittent rotation, or oscillatory pipe movement is commonly implemented to maintain hole cleaning efficiency [25].

Pipe eccentricity and centralization directly influence the annular flow profile and cuttings transport. Non-centralized drill strings create wide and narrow annular gaps, leading to low-velocity zones along the wide side where cuttings preferentially settle [5]. Centralizers, stabilizers, and properly spaced reamers can mitigate these effects by redistributing flow and generating turbulence in low-velocity regions, thereby minimizing stationary bed formation [3], [7]. In highly deviated sections, eccentricity can also interact with doglegs to produce localized zones of recirculation, where cuttings may accumulate despite overall sufficient annular velocity, highlighting the importance of integrated BHA design, centralization strategy, and fluid rheology optimization [4], [29].

The design of the bottomhole assembly (BHA) is a fundamental operational parameter affecting hole cleaning. Stabilizer placement, drill collars, and reamers modify the annular flow path and influence the generation of secondary currents and turbulence, which in turn affect cuttings suspension and removal efficiency [2], [12]. Optimized BHA configurations can improve hole cleaning by preventing cuttings accumulation behind the drill string and enhancing flow near the borehole wall [25]. Conversely, poorly designed BHAs may create stagnant zones that exacerbate cuttings deposition and increase torque-and-drag loads, particularly in extended reach and horizontal sections [13].

Operational practices such as circulation schedules, ramped pump rates, and periodic high-viscosity sweeps complement drilling fluid design and mechanical interventions to optimize hole cleaning [3], [28]. These practices ensure that cuttings remain suspended during low-flow periods, prevent bed consolidation, and allow effective removal of accumulated cuttings during dynamic operations. Integration of real-time monitoring tools, such as downhole flow sensors and cuttings concentration measurements, enables adaptive operational adjustments to maintain optimal hole cleaning performance in complex wellbore geometries [4], [8].

3. Method

This section presents the mathematical models and governing equations used to describe cuttings transport and hole cleaning in deviated and horizontal wellbores. The models account for the specific geometry of the wellbore, drill string configuration, and the rheological properties of the drilling fluid. Key parameters including annular velocity, fluid viscosity and density, yield stress, and drill string eccentricity are incorporated to accurately capture their influence on cuttings transport along the annulus.

The developed equations are applied to simulate cuttings removal dynamics under varying operational conditions, such as different mud flow rates, drill pipe rotation speeds, and well inclinations. These simulations provide quantitative insights into hole cleaning efficiency, identify sections of the wellbore prone to cuttings accumulation, and evaluate the impact of drilling parameters on annular pressure loss, cuttings bed formation, and particle suspension. The results form the basis for optimizing drilling fluid properties and operational strategies to ensure effective hole cleaning in complex well geometries.

3.1 Reynolds Number Model Development

The Reynolds number is a key parameter governing hole cleaning and cuttings transport in wellbores, as it defines the prevailing flow regime, laminar or turbulent. Laminar flow primarily supports cuttings transport, whereas turbulent flow is more effective for removing cuttings, particularly in areas prone to bed accumulation within deviated sections of the wellbore. Accurately determining the flow regime is therefore essential for optimizing wellbore cleaning efficiency. The three critical factors influencing the Reynolds number are mud weight, apparent or effective viscosity, and mud flow rate, all of which collectively dictate the hydraulic behavior of the drilling fluid and its ability to suspend and transport cuttings. The equation for Reynolds number for mud flow in the annulus is given as

$$R_{ea} = \frac{928(D_2 - D_1)\rho v_a}{\mu_{ea}} \tag{1}$$

Where D_2 is the inner diameter of the casing or open hole, inch, D_1 is the outer diameter of the pipe, inch, ρ is the weight of the drilling fluid, ppg, v_a is the velocity of the fluid in the annulus, μ_{ea} is the effective viscosity of the drilling fluid in the annulus

The velocity of the fluid is given as

$$v_a = \frac{Q}{2.448(D_2^2 - D_1^2)} \tag{2}$$

Where Q is the flowrate of the drilling fluid, gpm

Additionally, the effective viscosity of the drilling fluid in the annulus is given as

$$\mu_{ea} = 100K_a\left(\frac{144v_a}{(D_2 - D_1)}\right)^{n_a - 1}\left(\frac{2n_a + 1}{3n_a}\right)^{n_a} \tag{3}$$

$$n_a = 3.322 log\frac{(2PV + YP)}{(PV + YP)} \tag{4}$$

$$K_a = 511^{(1 - n_a)}(PV + YP) \tag{5}$$

Where n_a is the flow behaviour index of the fluid in the annulus, K_a is the consistency index of the fluid in the annulus, PV is the plastic viscosity of the fluid, cp, YP is the yield point of the fluid, Lb/100ft^2

3.2 Laminar Flow Regime

Laminar flow of fluid is effective for cuttings transport to the surface. Laminar flow is characterised by viscous flow at low

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flowrate. The high viscosity of the fluids enables adequate cuttings suspension as they are being transported to the surface.

For Laminar Flow, R< 2000.

Applying the laminar condition to equation 1 and making the mud apparent viscosity the subject of formula.

$$\frac{928(D_2-D_1)\rho v_a}{\mu_{ea}} < 2000 \quad (6)$$

$$\frac{928(D_2-D_1)\rho v_a}{2000} < \mu_{ea} \quad (7)$$

$$\mu_{ea} > \frac{928(D_2-D_1)\rho v_a}{2000} \quad (8)$$

$$\mu_{ea} > 0.464(D_2-D_1)\rho v_a \quad (9)$$

Substituting the value of Va into the equation gives

$$\mu_{ea} > 0.464(D_2-D_1)\rho\left(\frac{Q}{2.448(D_2^2-D_1^2)}\right) \quad (10)$$

$$\mu_{ea} > 0.464(D_2-D_1)\rho\left(\frac{Q}{2.448(D_2+D_1)(D_2-D_1)}\right) \quad (11$$

$$\mu_{ea} > \left(\frac{0.19\rho Q}{(D_2+D_1)}\right) \quad (12)$$

Putting equation 3.2 into equation 3.12 becomes

$$\frac{K_a(D_2-D_1)}{144(v_a)^{1-n_a}}^{1-n_a}\left(\frac{1+\frac{1}{n_a}}{0.0208}\right)^{n_a} > \left(\frac{0.19\rho Q}{(D_2+D_1)}\right) \quad (13)$$

Substituting the value of Va into the equation gives

$$\frac{K_a(D_2-D_1)^{1-n_a}}{144\left(\frac{Q}{2.448(D_2^2-D_1^2)}\right)^{1-n_a}}\left(\frac{1+\frac{1}{n_a}}{0.0208}\right)^{n_a} > \left(\frac{0.19\rho Q}{(D_2+D_1)}\right) \quad (14)$$

Making ρ the subject of the formula

$$\rho < \left(\frac{(D_2+D_1)}{0.19Q}\right)\left(\frac{K_a(D_2-D_1)^{1-n_a}}{144\left(\frac{Q}{2.448(D_2^2-D_1^2)}\right)^{1-n_a}}\right)\left(\frac{1+\frac{1}{n_a}}{0.0208}\right)^{n_a} \quad (15)$$

3.3 Turbulent Flow Regime

Turbulent flow of fluid is effective for cuttings removal from cuttings buildup zones. Turbulent flow is characterised by high flowrate and low viscosity fluids. The high flowrate of the fluids enables adequate cuttings removal from its buildup.

For Turbulent Flow, R>4000.

Applying the turbulent condition to equation 1 and making the mud apparent viscosity the subject of formula.

$$\frac{928(D_2-D_1)\rho v_a}{\mu_{ea}} > 4000 \quad (16)$$

$$\frac{928(D_2-D_1)\rho v_a}{4000} > \mu_{ea} \quad (17)$$

$$\mu_{ea} < \frac{928(D_2-D_1)\rho v_a}{4000} \quad (18)$$

$$\mu_{ea} < 0.232(D_2-D_1)\rho v_a \quad (19)$$

Substituting the value of Va into the equation gives

$$\mu_{ea} < 0.232(D_2-D_1)\rho\left(\frac{Q}{2.448(D_2^2-D_1^2)}\right) \quad (20)$$

$$< 0.232(D_2-D_1)\rho\left(\frac{Q}{2.448(D_2+D_1)(D_2-D_1)}\right) \quad (21)$$

$$\mu_{ea} < \left(\frac{0.0948\rho Q}{(D_2+D_1)}\right) \quad (22)$$

Substituting the value of Va into the equation gives

$$\frac{K_a(D_2-D_1)^{1-n_a}}{144\left(\frac{Q}{2.448(D_2^2-D_1^2)}\right)^{1-n_a}}\left(\frac{1+\frac{1}{n_a}}{0.0208}\right)^{n_a} < \left(\frac{0.0948\rho Q}{(D_2+D_1)}\right) \quad (23)$$

Making ρ the subject of the formula

$$\rho > \left(\frac{(D_2+D_1)}{0.0948Q}\right)\left(\frac{K_a(D_2-D_1)^{1-n_a}}{144\left(\frac{Q}{2.448(D_2^2-D_1^2)}\right)^{1-n_a}}\right)\left(\frac{1+\frac{1}{n_a}}{0.0208}\right)^{n_a} \quad (24)$$

3.4 Hole Cleaning Evaluation Parameters

There are parameters used to evaluate the condition of the hole and the efficiency of the hole cleaning and cuttings transport.

3.4.1 Cuttings Transport Index

The cuttings transport index (CCI) is given as

The cuttings carrying index (CCI) is vertical well is given as

$$CCI = \frac{K_a \rho v_a}{400000} \quad (25)$$

Where Va is the fluid velocity, ft/min

3.4.2 Cuttings concentration

The cuttings concentration is given by

$$C_a = \frac{ROP d_b^2}{(V_a-V_s)(d_h^2-d_h^2)} \quad (26)$$

Where Ca is the cuttings concentration, dimensionless, Va is the velocity of the mud, ft/sec, Vs is the slip velocity, ft/sec, db is the diameter of the bit, in, dh is the diameter of the hole, in, dp is the pipe external diameter, in

3.4.3 Calculating Slip Velocity

The particle Reynolds number is given as

$$R_p = 15.47\frac{d_s \rho_f v_{sl}}{\mu_a} \quad (27)$$

Where, R_p is Particle Reynolds Number, dimensionless, v_{sl} = particle slip velocity, ft/sec, ρ_f = Fluid density, ppg, ρ_s = solids density, ppg, d_s = diameter of solids, in μ_a = the apparent viscosity of the fluid, cP

For turbulent flow i.e. particle Reynolds numberRp> 2000 and drag coefficient Cd = 1.5, the slip velocity is given as

$$V_s = 92.4\sqrt{\frac{d_s(\rho_c-\rho_f)}{C_d \rho_f}} \quad (28)$$

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For 3<Rp<300 i.e. at intermediate flow regime, then the slip velocity in ft/sec is given by

$$V_s = \frac{175 d_s(\rho_c - \rho_f)^{0.667}}{\mu_a{}^{0.333}\rho_f{}^{0.333}} \quad (29)$$

But for laminar flow, i.e. Rp< 3, then the slip velocity is given as

$$V_s = 4980 d_s^2 \frac{(\rho_c - \rho_f)}{\mu_{ea}} \quad (30)$$

Noah's equation for cutting bed height is given as

$$H_t = \alpha + \beta e^{-\gamma t} \quad (31)$$

Where, α= Residual bed height corresponding to infinite circulation time , t = cuttings bed erosion time, β = Residual bed height, K = fluid Consistency Index

$$\gamma = n/k \quad (32)$$

The formula for cuttings bed erosion time is given as

$$t = \frac{1}{\gamma}\frac{H_t - \alpha}{\beta} \quad (33)$$

3.5 Simulation

Model simulation was done to determine several parameters that affects cuttings transport in the wellbore based on the models presented. The simulation of the model was done using Matlab R2014 software. Matlab is a scientific and engineering software that enables modelling, optimisation and analysis. It also has a programming environment where users write functions and script files executed in the command window.

The simulation procedure adopted in this study is described by the block diagram given below:

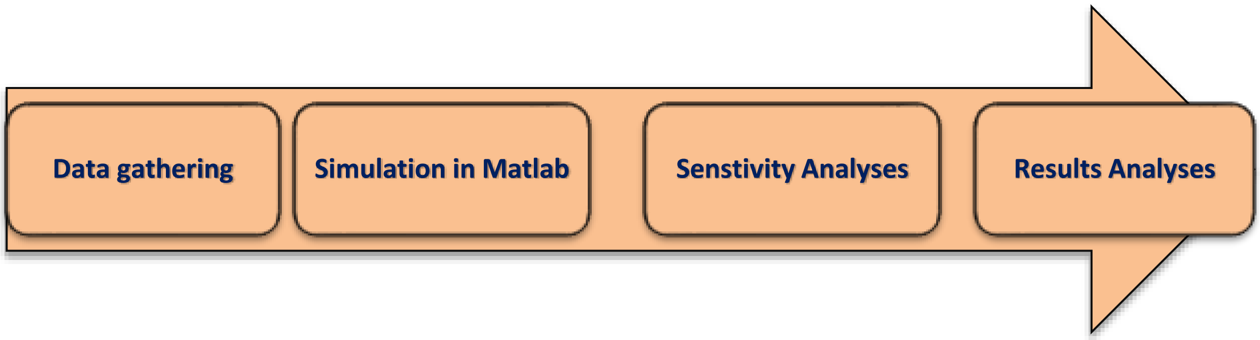

Figure 1: Block diagram of simulation procedure

The data comprises fluid data which includes the fluid rheological data, the string data, the well trajectory data

Table 1: Rheological data

Activity	Base
600RPM	46
300RPM	30
200RPM	22
100RPM	18
6RPM	11
3RPM	8
Mud Flowrate, Q, gpm	600
Mud Density, ppg	9.1
Plastic viscosity, cp	18
Yield Point, Lb/100ft	32

The string data during the drilling process is given in table 3.2

Table 2: Drillstring data

TYPE	LENGTH		BODY		STB/TOOL JOINT			LINEAR WEIGHT		GRADE	MATERIAL	CLASS
	PIPE	TOTAL	OD	ID	OD	ID	Length	NOM	ACTUAL			
	[ft]	[ft]	[in]	[in]	[in]	[in]	[in]	[lb/ft]	[lb/ft]	[psi]		
Pipe	6780.94	6780.9	5	4.28	6.312	2.75	28.9	19.5	19.5	135000	CS	P
Hevi-Wate DP	370.73	7151.7	5	3	6.5	3	20	49.7	49.7	55000	CS	

Hevi-Wate DP	1010.14	8161.8	3.5	2.25	4.75	2.313	20	23.2	23.2	55000	CS	
Jar	12.5	8174.3	4.75	2.06	-	-	20	37.5	37.5	110000	CS	
Hevi-Wate DP	367.29	8541.6	3.5	2.25	4.75	2.313	20	23.2	23.2	55000	CS	
Pipe	2577.76	11119.4	3.5	2.76	4.812	2.125	29.9	13.3	13.3	135000	CS	P
Hevi-Wate DP	30.51	11149.9	3.5	2.06	4.75	2.125	20	25	25	55000	CS	
MWD	61.35	11211.2	4.75	1.92	-	-	29.9	50	50	110000	SS	
Hevi-Wate DP	10.17	11221.4	3.5	2.25	4.75	2.188	20	25	25	55000	CS	
Stabilizer	1.15	11222.5	4.75	2.25	5.75	2.19	3.3	40	40	110000	CS	
PDM	26.25	11248.8	4.75	2	-	-	29.9	42.91	42.91	110000	CS	
BIT	0.66	11249.4	6	0	-	-		0	0	0	CS	

The profile of the well is given in figure 2 below.

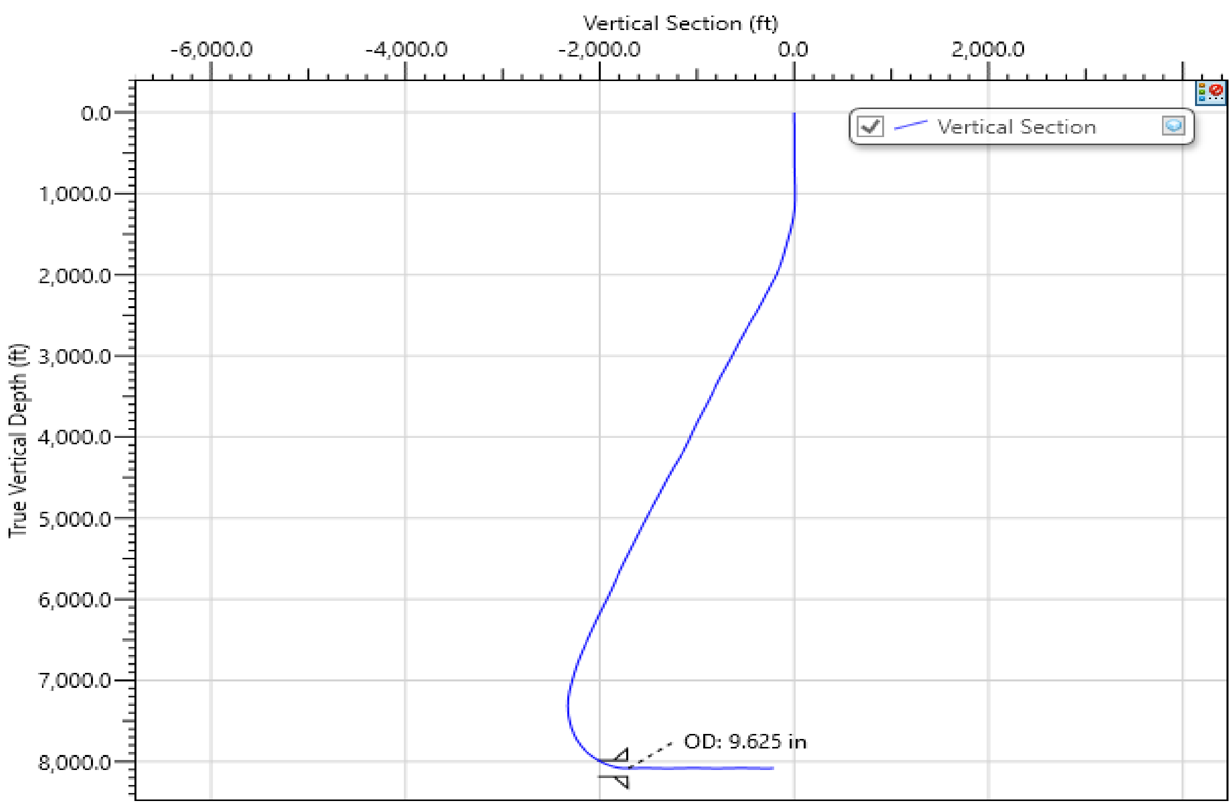

Figure 2: Profile of Well

4. Results and Discussion

This section presents and discusses the results of hole cleaning simulations conducted for deviated well configurations. Efficient hole cleaning is a critical challenge in deviated and horizontal drilling, as poor cuttings transport can lead to excessive annular accumulation, elevated torque and drag, stuck pipe incidents, reduced drilling efficiency, and in severe cases, total wellbore compromise. The simulations in this study were designed to assess hole cleaning performance under varying operational and fluid conditions, with a focus on identifying the key parameters that govern cuttings transport efficiency.

The analysis specifically examined the influence of drilling fluid rheology including plastic viscosity, yield point, and flow index on the annular carrying capacity, alongside the effects of mud density on cuttings suspension. The impact of flow regime transitions, from laminar to turbulent conditions, was also investigated to evaluate their relative importance for hole cleaning efficiency across different well inclinations. Additional factors, such as cuttings bed erosion time and bed height, were incorporated into the study to provide a more comprehensive understanding of cuttings transport dynamics. Results are presented using metrics such as the Cuttings Carrying Index (CCI) and transport ratios along the wellbore, highlighting how variations in rheological properties, fluid flow rates, and operational parameters influence cuttings removal. Comparative evaluations across different scenarios reveal threshold conditions necessary to achieve effective hole cleaning, optimize annular transport, and mitigate operational risks in deviated well drilling.

4.1 Plastic Viscosity Vs Cuttings Carrying Capacity

The effect of plastic viscosities of mud samples on the cuttings carrying index were investigated. This shown in figure 4.1.

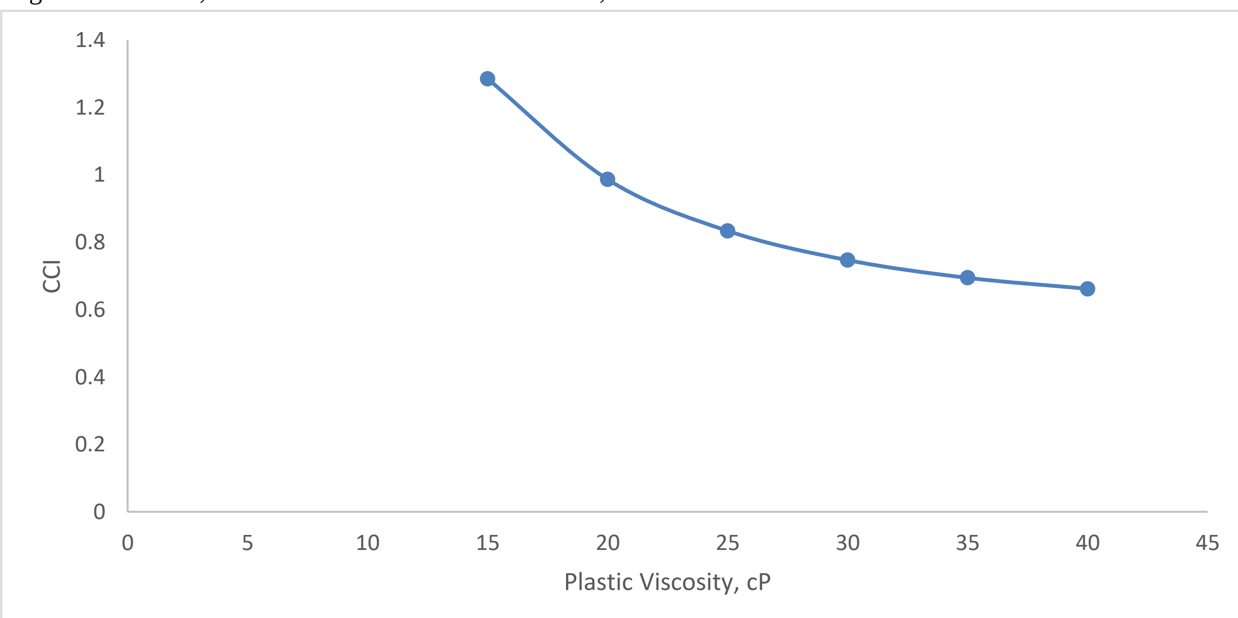

Figure 3: CCI as a function of PV

Figure 3 illustrates that the Cuttings Carrying Index (CCI) exhibits an inverse relationship with plastic viscosity (PV), with higher PV values corresponding to lower CCI, indicating reduced efficiency in suspending and transporting cuttings along the annulus. This behavior can be attributed to the hydrodynamics of viscous fluids in deviated wellbores. While increasing PV enhances the base fluid's viscosity and improves suspension at low shear rates, it simultaneously increases flow resistance, suppressing annular velocity and reducing turbulence. The net effect is diminished cuttings transport and a corresponding decline in CCI.

From a theoretical perspective, this observation aligns with established drilling fluid hydraulics principles. Rheological models, such as Bingham Plastic and Herschel–Bulkley, show that higher PV raises the apparent viscosity at a given shear rate, limiting annular velocity gradients and turbulence intensity both critical for effective hole cleaning. Practically, overly viscous muds can exacerbate pressure losses, decrease pump efficiency, and hinder cuttings transport by restricting the fluid's ability to generate sufficient annular velocity.

The effect is particularly pronounced in deviated wells, where cuttings naturally settle along the low side of the borehole due to gravity. While moderate PV values promote suspension stability, excessively high PV impedes hydraulic transport, reducing CCI and increasing the risk of cuttings bed formation. These findings emphasize the operational need to optimize PV in conjunction with other rheological properties, such as yield point, to balance suspension stability with effective cuttings transport and overall drilling efficiency.

Table 3: Numerical values of PV vs CCI

PV	**CCI**
15	1.285402
20	0.986753
25	0.834085
30	0.747193
35	0.694723
40	0.662239

Table 3 summarizes the computed relationship between plastic viscosity (PV) and the Cuttings Carrying Index (CCI), revealing a clear inverse correlation. As PV increases from 15 cP to 40 cP, the CCI decreases from 1.2854 to 0.6622, representing an overall reduction of approximately 48.5% across the tested range. This trend highlights the critical influence of PV on hole cleaning efficiency, emphasizing the need for careful rheological design. Operationally, the results indicate that an optimal PV window exists: while excessively low PV can compromise suspension and cuttings bed erosion, excessively high PV beyond approximately 30–35 cP in this simulation—significantly reduces CCI, increasing the risk of cuttings bed accumulation, pack-off, and elevated equivalent circulating density (ECD). Maintaining PV within a moderate range is therefore essential to achieve a balance between effective suspension of cuttings and efficient annular transport, ensuring optimal drilling performance and wellbore integrity.

4.1 Effect of Mud Weight on CCI.

The mud weight was systematically varied through the controlled addition of barite and other conventional weighting materials to assess its influence on the Cuttings Carrying Index (CCI) under deviated well conditions. Mud weight is a fundamental hydraulic parameter in drilling operations, as it directly affects bottomhole pressure, equivalent circulating density (ECD), and the overall efficiency of cuttings transport. Maintaining an appropriate mud density is essential to balance formation pressures and ensure wellbore stability, yet excessive increases can adversely affect hole cleaning by altering fluid rheology and modifying the flow regime.

Investigating the effect of mud weight on CCI is particularly important because higher-density muds typically exhibit increased apparent viscosity and reduced annular velocities at a constant pump rate. These changes can suppress turbulence and limit the fluid’s ability to suspend cuttings, especially in inclined and horizontal well sections where gravitational settling is more pronounced. Conversely, muds with excessively low density may enhance annular velocity and turbulence, improving cuttings transport, but pose well control risks such as influx, borehole collapse, or differential sticking.

By analyzing the relationship between CCI and mud weight, this study highlights the operational trade-offs between maintaining hydrostatic balance and achieving efficient hole cleaning. The results allow for the identification of an optimal mud weight range that provides sufficient wellbore support while sustaining effective cuttings transport. This optimization is critical in deviated drilling scenarios, where inadequate hole cleaning can quickly lead to pack-off, stuck pipe, and costly non-productive time (NPT).

Therefore, simulating the variation of mud weight on CCI serves not only to quantify its direct impact on cuttings transport but also to inform practical drilling fluid design. The findings provide guidelines for achieving a balanced drilling program that integrates well control, hydraulic efficiency, and hole cleaning, ultimately enhancing well integrity and overall drilling performance.

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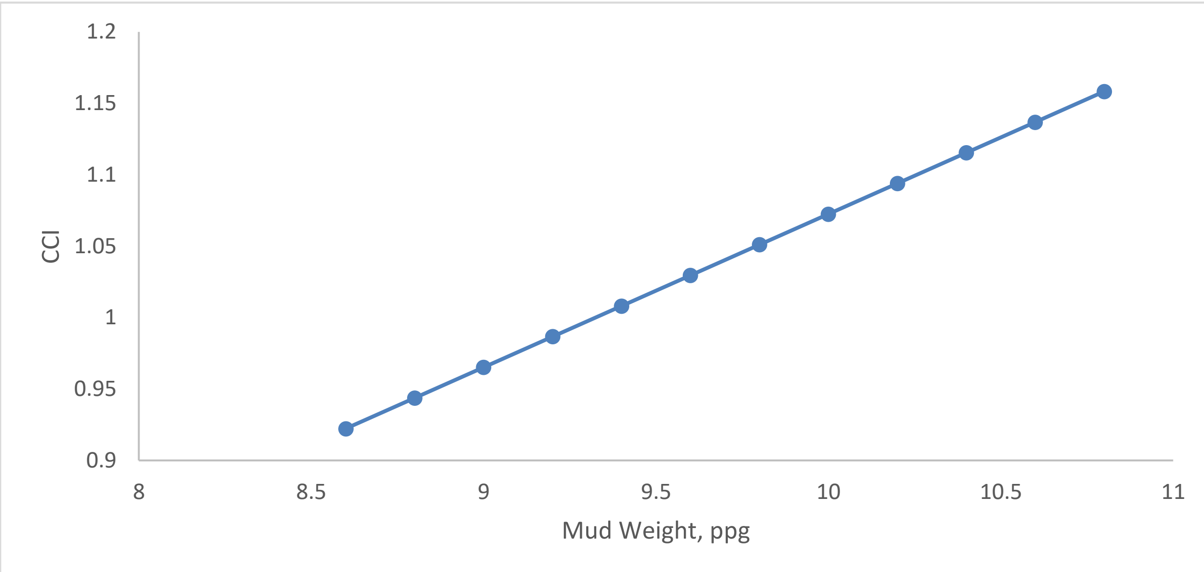

Figure 4: Mud Weight vs CCI

Figure 4 illustrates the relationship between mud weight and the Cuttings Carrying Index (CCI), showing a clear direct proportionality. As the mud density increases from 8.6 ppg to 9.6 ppg, the CCI correspondingly rises from 0.9224 to 1.0297, representing an approximate 11.6% improvement in cuttings transport efficiency. This trend indicates that higher-density mud systems enhance the drilling fluid's capacity to suspend and transport cuttings effectively, particularly in deviated wellbores where gravitational settling is more pronounced.

The observed behavior is consistent with both theoretical principles and practical drilling experience. Increasing mud weight elevates the hydrostatic pressure and, critically, improves the carrying capacity of the fluid through enhanced buoyancy effects on the cuttings. Under laminar or transitional flow conditions, denser fluids are more capable of lifting particles, resulting in higher CCI values. Since CCI serves as a dimensionless measure of a fluid's efficiency in transporting cuttings, its increase with mud weight demonstrates that heavier muds provide a more effective medium for cuttings transport at a given annular velocity.

However, the positive impact of increased mud density must be considered alongside operational limitations. Excessive mud weights can significantly raise the equivalent circulating density (ECD), increasing the risk of formation fracturing, lost circulation, or differential sticking, particularly in weak or depleted formations. Additionally, the incorporation of high concentrations of weighting materials, such as barite, may modify the rheological properties of the mud, raising plastic viscosity and yield point which can reduce annular velocity and increase pump pressure requirements.

Therefore, while higher mud weights clearly improve CCI and hole cleaning efficiency, the operational benefits must be carefully balanced against the potential risks associated with over-weighted fluids. Optimizing mud density within a safe and effective range is essential to maintain efficient cuttings transport while preserving wellbore stability and minimizing the likelihood of drilling complications.

4.3. Effect of Mud Flowrate on CCI at varying mud weight

The effect of varying mud flowrates on the Cuttings Carrying Index (CCI) was examined to evaluate the hydraulic efficiency of the circulating system in deviated wellbores. Mud flowrate is a key operational parameter influencing hole cleaning, as it directly determines annular velocity and the shear forces acting on cuttings within the wellbore. Higher flowrates increase turbulence and enhance the suspension capacity of the drilling fluid, promoting more effective cuttings transport. This effect is especially critical in inclined and horizontal sections, where gravitational settling of cuttings is more pronounced and the risk of bed formation is greater. In contrast, insufficient flowrates may result in inadequate cuttings removal, leading to cuttings accumulation, stuck pipe, increased torque and drag, and ultimately reduced drilling efficiency.

This investigation addresses two main practical concerns. Firstly, the hydraulic energy imparted by the circulating mud system is the primary mechanism for transporting cuttings to the surface; therefore, determining the optimal flowrate is essential to achieve effective hole cleaning while avoiding operational constraints such as pump capacity limitations and excessive pressure losses. Secondly, in deviated well geometries, annular cross-sections and flow regimes vary along the wellbore, making the relationship between flowrate and CCI particularly complex. By analyzing how changes in mud flowrate influence CCI, it is possible to assess whether the system operates within laminar, transitional, or turbulent

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flow regimes, each of which has distinct implications for cuttings suspension and transport efficiency.

Consequently, evaluating the effect of mud flowrate on CCI is both theoretically sound and practically necessary. The insights gained provide a basis for optimizing key drilling parameters, including pump rates, annular velocities, and equivalent circulating density (ECD), to establish an operational window that balances efficient hole cleaning with safe, cost-effective drilling hydraulics. This understanding is particularly important in complex well trajectories, where precise control of fluid dynamics directly impacts wellbore stability, drilling efficiency, and the prevention of non-productive time (NPT).

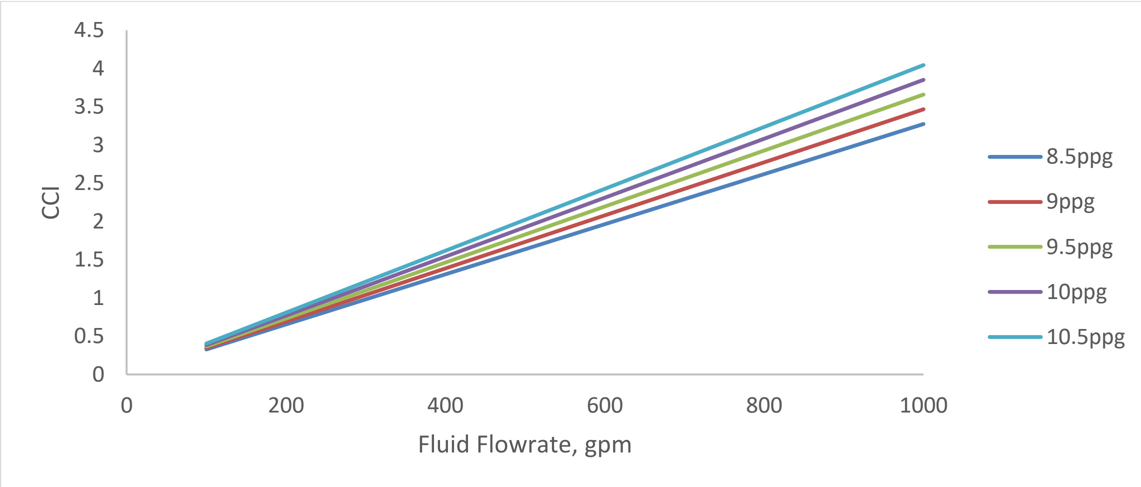

Figure 5: Flowrate Vs CCI at varying mud weight

Figure 5 illustrates the relationship between mud flowrate and the Cuttings Carrying Index (CCI) across different mud weight conditions, revealing a clear and almost linear increase in CCI with increasing flowrate. At low flowrates, around 200 gpm, the CCI values are relatively low and closely clustered across all tested mud weights, ranging from approximately 0.3 to 0.6. This indicates that, within this lower hydraulic energy range, flowrate is the dominant factor influencing cuttings transport, while the impact of mud weight is minimal. Under these conditions, the annular velocity is insufficient to fully mobilize the benefits of higher fluid density or enhanced rheology, and the transport of cuttings is largely governed by the kinetic energy imparted by the circulating fluid.

As the flowrate is increased toward higher levels, approaching 1000 gpm, the CCI rises substantially, reaching values between approximately 3.2 and 4.0, depending on the mud weight employed. This significant increase reflects the stronger shear forces and higher annular velocities generated at elevated flowrates, which enhance the ability of the drilling fluid to suspend and transport cuttings upward through the annulus. The effect of mud weight also becomes increasingly apparent at these higher flowrates. For instance, at 1000 gpm, the CCI for a heavier mud of 10.5 ppg reaches around 4.0, compared to approximately 3.2 for a lighter mud of 8.5 ppg, representing an improvement of roughly 25% in cuttings carrying capacity. This enhancement can be attributed to the combined effect of higher fluid density and slightly increased apparent viscosity, which reduces the settling velocity of particles and improves suspension stability, particularly in deviated and horizontal well sections where gravitational settling is more pronounced.

The interaction between flowrate and mud weight demonstrates a synergistic effect on hole cleaning efficiency. At lower flowrates, mud weight contributes little to cuttings transport efficiency because the kinetic energy in the annulus is insufficient to leverage the suspension benefits of denser muds. Conversely, at higher flowrates, the increased turbulence enhances the effectiveness of heavier muds, resulting in a compounded improvement in cuttings transport. From a theoretical perspective, these trends align with hydraulics principles: higher flowrates increase annular velocity and Reynolds number, promoting turbulence, which is more effective at maintaining particles in suspension. Simultaneously, higher mud weights reduce the slip velocity of cuttings according to Stokes' Law, further improving suspension efficiency.

In practical drilling operations, this relationship has critical implications for the optimization of hole cleaning strategies. Operators frequently adjust pump rates in conjunction with mud weight to achieve a balance between hydraulic energy and suspension capacity. This is particularly important in inclined and horizontal wells, where cuttings beds are more prone to form, and efficient transport requires careful calibration of both flowrate and fluid properties. By understanding and exploiting the synergistic interaction between flowrate and mud weight, drilling engineers can enhance the CCI, minimize the risk of cuttings accumulation, and improve overall operational efficiency and wellbore stability.

4.4. Maximum Mud weight for Laminar Flow

In this section, the maximum mud weight required to sustain laminar flow in the wellbore annulus was investigated. The simulation aimed to identify the threshold mud density that provides adequate hydrostatic support to the formation while maintaining a flow regime that minimizes excessive pressure losses. This investigation is critical because mud weight directly influences the balance between wellbore stability and hydraulic efficiency, both of which are key to safe and effective drilling operations.

If the mud weight is too low, the hydrostatic column may be insufficient to counteract formation pore pressure, increasing the risk of wellbore collapse, influx, or blowouts. Conversely, excessively high mud weight elevates the equivalent circulating density (ECD), potentially causing lost circulation, differential sticking, or fracturing of the formation. Therefore, establishing the safe operational window for mud weight is essential to ensure that the drilling fluid simultaneously stabilizes the wellbore and supports efficient circulation.

The simulation focused not only on identifying the mud weight range that preserves laminar flow but also on evaluating how variations in density influence the Reynolds number and the subsequent transition between laminar, transitional, and turbulent flow regimes. Laminar flow is advantageous in reducing pump energy requirements and minimizing erosion of the wellbore and tubular surfaces. However, in deviated wells, laminar conditions may limit cuttings suspension and transport, highlighting the need to optimize the flow regime to enhance hole cleaning efficiency.

By determining the maximum mud weight permissible for laminar flow, this analysis provides practical guidelines for drilling fluid design. It ensures that fluid density is sufficient to prevent well control issues while remaining compatible with hydraulic objectives, including managing pressure losses, improving circulation efficiency, and maintaining stable wellbore conditions. This consideration is especially critical in deviated wells, where challenges in hole cleaning are amplified and the careful selection of mud properties is a decisive factor for operational success.

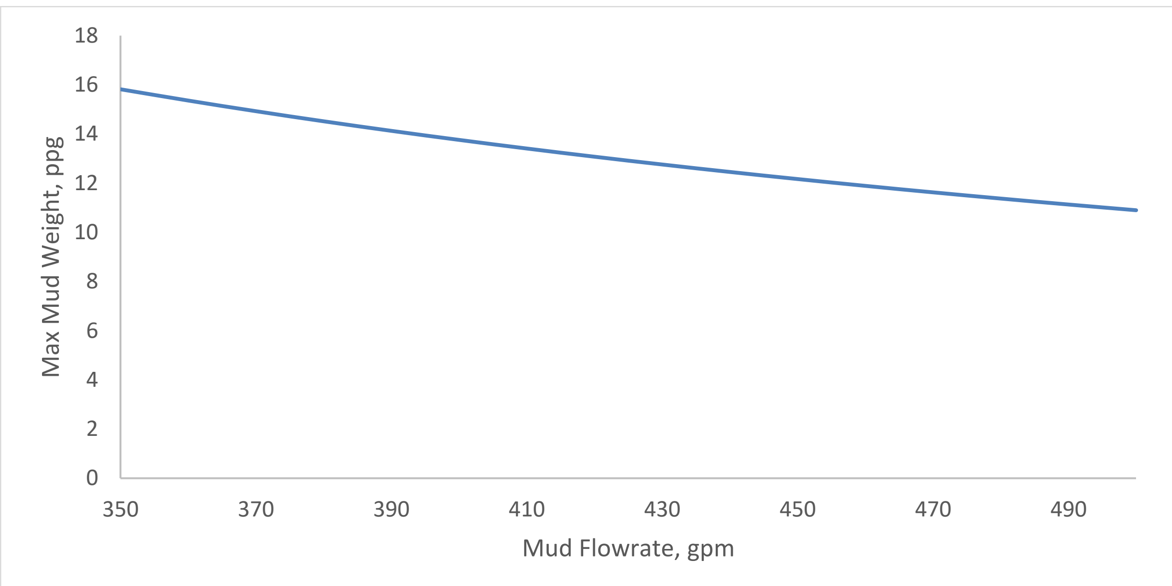

Figure 6: Maximum Mud Weight for Laminar Flow

Figure 6 illustrates the variation of the maximum mud weight required to sustain laminar flow as a function of mud flowrate. The trend indicates that as the flowrate increases, the maximum mud weight that permits laminar flow decreases. This behaviour can be understood by considering the interplay between mud weight, viscosity, flow regime, and the Reynolds number (Re). The Reynolds number increases with higher flowrates and fluid density but decreases with higher viscosity. At elevated flowrates, inertial forces dominate over viscous forces, pushing the flow regime toward turbulence. Consequently, sustaining laminar flow at high circulation rates would require unrealistically high mud weights or viscosities to counteract the turbulence-inducing inertial effects.

Theoretically, this observation aligns with fluid mechanics principles. At low flowrates, laminar flow can be maintained over a wider range of mud weights because inertial forces are weak and viscous forces dominate. As pump rates increase, even moderate increases in mud weight elevate the Reynolds number, accelerating the transition from laminar to turbulent flow. Therefore, the maximum mud weight threshold for laminar flow naturally decreases as flowrate rises.

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From a practical drilling perspective, these results are consistent with operational realities. In the field, mud weight is often increased to provide hydrostatic support in deeper formations, while higher pump rates are simultaneously applied to enhance hole cleaning, especially in deviated and horizontal wells. The combination of higher mud weight and increased circulation rate makes laminar flow virtually unattainable under typical drilling conditions. As a result, drilling engineers generally aim for transitional or turbulent flow regimes, accepting higher pressure losses as a necessary trade-off for effective cuttings transport.

Overall, the simulation confirms both theoretically and practically that the range of mud weights allowing laminar flow narrows with increasing flowrate. In real-world drilling operations, laminar flow is rarely maintained at high pump rates, and design considerations instead focus on achieving controlled turbulent or transitional flow regimes that optimize hydraulic efficiency while ensuring effective hole cleaning.

4.5 Minimum mud weight for turbulent flow

The investigation of the minimum mud weight required to sustain turbulent flow was conducted to define the hydraulic thresholds critical for efficient cuttings transport and wellbore cleaning during drilling operations. Turbulent flow is generally more effective than laminar flow in suspending and transporting drilled cuttings because the chaotic eddies generated under turbulence enhance the carrying capacity of the fluid and minimize the deposition of cuttings beds. Identifying the minimum mud weight necessary to achieve turbulence therefore provides essential guidance for establishing the operational window for optimizing drilling fluid performance.

Theoretically, the transition from laminar to turbulent flow is governed by the Reynolds number, which depends on fluid velocity, viscosity, density, and the characteristic diameter of the wellbore. Mud weight directly influences this transition by affecting fluid density and rheological behavior, both of which alter the Reynolds number. Through simulation, the minimum mud weight at which turbulence is achieved can be determined, establishing baseline conditions for maintaining turbulent flow at practical pump rates, particularly in high-angle and horizontal wells where cuttings transport is inherently more challenging.

Practically, this investigation is crucial because operating below the identified mud weight threshold may result in laminar or transitional flow, leading to poor hole cleaning, cuttings bed accumulation, and increased risk of stuck pipe. Conversely, maintaining mud weight above the minimum ensures turbulent flow, promoting effective cuttings transport while avoiding excessive fluid density that could elevate equivalent circulating density (ECD) or induce formation fracturing. The analysis therefore provides a critical framework for balancing hydraulic efficiency with wellbore stability, enabling drilling engineers to optimize both mud weight and pump capacity to sustain desirable flow regimes.

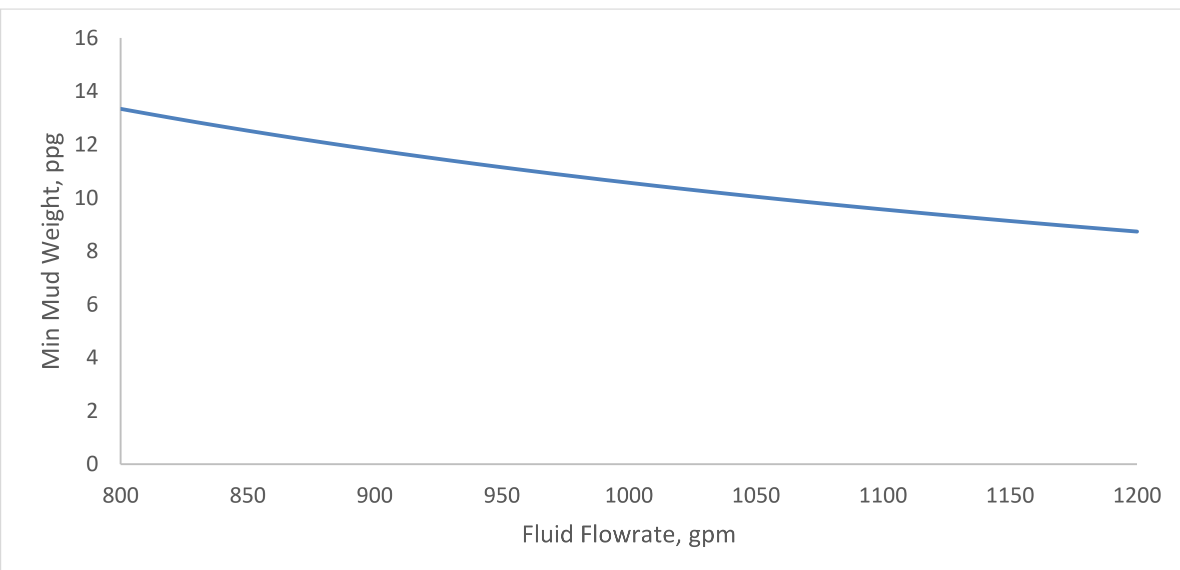

Figure 7: Minimum Mud Weight Corresponding to Specified Flowrate for Turbulent Flow

Figure 7 illustrates the relationship between mud flowrate and the minimum mud weight required to sustain turbulent flow, showing a clear inverse trend: as flowrate increases, the minimum mud weight needed for turbulence decreases. This behavior can be explained both theoretically and practically. From a fluid mechanics perspective, turbulence onset is governed by the Reynolds number ($Re = \rho VD/\mu$), which rises with increasing fluid velocity. At higher flowrates, even a relatively low-density fluid (lower mud weight) can achieve turbulence, as inertial forces dominate over viscous forces. Consequently, elevated flowrates reduce the dependence on mud weight to maintain turbulent conditions.

From a drilling hydraulics standpoint, this finding is particularly practical. Higher pump rates facilitate sustained turbulence even with lighter drilling muds, enabling efficient cuttings transport without the need to increase mud density unnecessarily. Maintaining lower mud weights at higher flowrates is advantageous, as excessive mud density can lead to formation damage, elevated equivalent circulating density (ECD), lost circulation, or wellbore fracturing.

Conversely, at lower flowrates, turbulence becomes more difficult to achieve due to reduced fluid velocity. Under such conditions, a higher mud weight is required to raise the Reynolds number sufficiently and initiate turbulence, consistent with the trend shown in Figure 7.

Overall, this result aligns with fluid dynamics principles and offers practical guidance for drilling operations. It highlights the trade-off between flowrate and mud density, providing engineers with a framework to optimize hydraulic conditions that ensure effective cuttings transport while preserving wellbore stability and formation integrity.

4.6. Effect of Cutting bed height on Cuttings bed erosion time as a function of Mud Viscosity

The erosion time of the cuttings bed height was examined across low, medium, and high-viscosity mud systems. Simulation results reveal that the rate of cuttings bed erosion is strongly influenced by drilling fluid viscosity, with direct implications for hole cleaning efficiency in deviated wells. This analysis underscores the trade-off between viscosity and effective cuttings transport. While high-viscosity muds are typically considered favorable for particle suspension, the findings indicate that excessive viscosity can hinder dynamic erosion, extending erosion times and increasing the risk of cuttings bed accumulation. Conversely, very low-viscosity fluids may enhance erosion rates but lack sufficient carrying capacity to transport cuttings effectively to the surface.

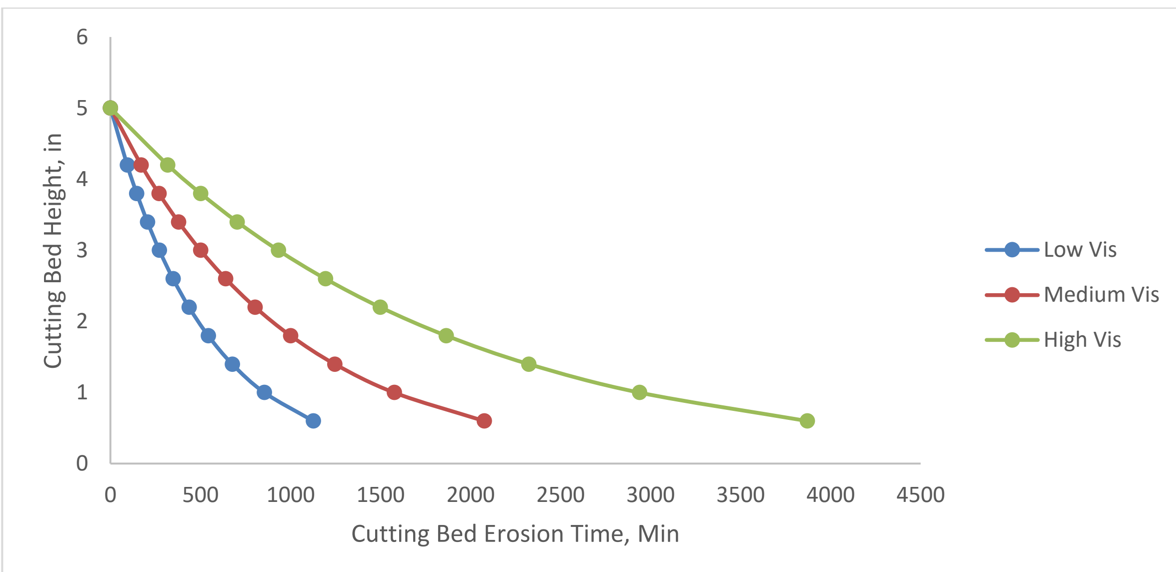

Figure 8: Cuttings bed erosion time vs Height as various mud viscosities

Figure 8 illustrates the variation of cuttings bed erosion time with different mud viscosities. For low-viscosity muds, the erosion time is relatively short because these fluids offer lower resistance to flow and achieve higher annular velocities under the same pumping conditions. The enhanced velocity profile generates sufficient shear forces along the wellbore, promoting rapid resuspension and transport of settled cuttings. However, despite the fast erosion rate, excessively low viscosity can reduce the fluid's carrying capacity, potentially leading to re-deposition of cuttings further up the annulus.

Medium-viscosity muds exhibit a balanced erosion time, reflecting moderate cuttings removal efficiency. These muds provide an optimal compromise between suspension capacity and flow velocity, allowing effective transport of cuttings while maintaining adequate shear forces to erode the bed. This viscosity range often represents the operational sweet spot in drilling, where hole cleaning efficiency and hydraulic energy usage are optimized.

High-viscosity muds, on the other hand, show significantly longer erosion times. While higher viscosity improves static suspension and prevents settling under low-flow conditions, it also dampens annular velocity, reducing the shear forces acting on the cuttings bed. As a result, erosion of settled particles becomes more difficult, particularly in deviated or horizontal sections where gravitational settling is pronounced. Although high-viscosity muds excel at maintaining cuttings in suspension under static conditions, they are less effective for actively removing cuttings beds during circulation.

5. Conclusion

This study provides a comprehensive evaluation of the hydraulic and rheological factors governing hole cleaning efficiency in deviated wellbores, emphasizing the relationship between mud rheology, mud density, flowrate, and cuttings transport dynamics. The findings demonstrate that hole cleaning performance, quantified through the Cuttings Carrying Index (CCI) and related metrics, is not controlled by a single parameter in isolation but rather emerges from the interaction of interdependent fluid and hydraulic properties. The analysis revealed that plastic viscosity (PV) negatively impacts CCI. Increasing PV from 15 cP to 40 cP led to a nearly 50% reduction in CCI, highlighting the hydrodynamic penalty of excessive viscosity. While higher viscosity improves static suspension of cuttings, it simultaneously suppresses annular velocity and turbulence, limiting cuttings transport. These results underscore the operational need for moderate viscosity levels that provide sufficient suspension without compromising hydraulic efficiency.

In contrast, mud weight (MW) exhibited a direct, positive correlation with CCI. Increasing MW from 8.6 ppg to 9.6 ppg enhanced CCI by approximately 11.6%, primarily due to increased buoyancy and reduced slip velocity, which improve particle suspension. However, excessive MW introduces operational risks, including elevated equivalent circulating density (ECD), lost circulation, and potential formation damage. Therefore, while higher mud weight improves cuttings transport, it must be optimized within safe operational limits. The combined effect of flowrate and mud weight demonstrated a synergistic influence on hole cleaning efficiency. Higher flowrates consistently improved CCI by increasing annular velocity and turbulence, with the effect further amplified at elevated mud weights. For example, at flowrates near 1000 gpm, increasing MW from 8.5 to 10.5 ppg improved CCI by nearly 25%. These results highlight the importance of simultaneously optimizing hydraulic energy and fluid density to achieve efficient cuttings transport in deviated well geometries.

Flow regime analysis provided additional insights into the role of mud weight in controlling laminar–turbulent transitions. As flowrate increased, the maximum MW capable of sustaining laminar flow decreased, while the minimum MW required to maintain turbulence also declined. This indicates that turbulence, which favors suspension and erosion, can be maintained at higher flowrates even with relatively light muds, offering operators a controllable operational envelope for efficient hole cleaning.

Investigation of cuttings bed erosion time further emphasized the critical influence of viscosity. Low-viscosity muds promoted rapid erosion due to strong velocity profiles but compromised suspension stability. Conversely, high-viscosity muds enhanced static suspension but prolonged erosion times by reducing annular velocity. Medium-viscosity systems achieved the best balance, enabling effective cuttings bed erosion while maintaining reliable transport, an essential consideration for deviated wells where bed formation is unavoidable.

Overall, this study quantitatively links mud rheology, density, and hydraulics with CCI behavior and flow regime transitions. The results confirm that optimal hole cleaning is achieved not by altering a single parameter, but through coordinated optimization of viscosity, density, and flowrate within defined operational windows. Integrating CCI analysis with laminar–turbulent transition behavior provides a robust framework for designing practical drilling envelopes that safeguard wellbore stability, minimize non-productive time (NPT), and enhance overall drilling efficiency.

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