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A Computational Fluid Dynamics Study on the Effect of Drilling Parameters on Wellbore Cleaning in Oil Wells

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Abstract: Poor wellbore cleaning is a significant challenge in oil drilling, primarily due to the accumulation of cuttings at the bottom of the well, particularly in deviated and horizontal wells. This study addresses this issue by employing Computational Fluid Dynamics (CFD) with the commercial software ANSYS FLUENT (2023-R1) to simulate a solid–liquid multiphase flow in an annulus. The primary objective is to analyze the cuttings concentration, pressure loss, and solid velocity profiles across various drilling parameters, including drill pipe rotation, the flow rate, rate of penetration, inclination angle, and fluid rheology. Our results underscore the critical role of these parameters in enhancing cuttings transport efficiency. Specifically, the drill pipe rotation, flow rate, and rate of penetration emerge as the most influential factors affecting the wellbore cleaning performance. With a validated model exhibiting an average error of 4.24%, this study provides insights into optimizing drilling operations to improve wellbore cleaning and increase hydrocarbon recovery.

Keywords: oil drilling; wellbore cleaning; cuttings; Computational Fluid Dynamics (CFD); ANSYS FLUENT; multiphase flow; cuttings concentration; pressure loss; solid velocity

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1. Introduction

Directional drilling is extensively employed in the oil and gas sector, both onshore and offshore, providing precise wellbore positioning, enhanced resource extraction, and a reduced environmental footprint [1]. This technique is particularly valuable for accessing reserves in inaccessible locations while avoiding densely populated regions. It also allows for greater flexibility in drilling, completion, and production processes, even in the most unconventional reservoirs [2]. A key factor in the success of directional drilling is effective wellbore cleaning, which is critical for the optimal transportation and removal of cuttings via appropriate drilling fluids. Cuttings often accumulate on the lower side of the annulus between the casing and the drill pipe, where constricted flow areas can exacerbate removal difficulties. Without effective management, these accumulations can form beds of cuttings that may lead to complications such as stuck pipes, a restricted flow within the annulus, and reduced drilling rates, potentially culminating in well abandonment [3].

Despite numerous numerical studies in the literature aimed at understanding the transport of cuttings during drilling, the ongoing challenge of insufficient wellbore cleaning, especially in horizontal and deviated wells, continues to be a significant concern for the drilling industry [4]. This underscores the need for further research to enhance our understanding of cuttings transport mechanisms and to assess the effectiveness of drilling fluids within the annular space.

Developing reliable models for cuttings transport requires extensive experimental data that mirror the flow conditions typically encountered in actual drilling operations. However, accurately resolving the flow equations for real wellbores is often impractical due to the extensive computational resources needed [5]. While the well geometry in this study does not completely match the dimensions of annular spaces found in typical drilling operations, the structural characteristics and operational parameters we used closely reflect real-world conditions. This approach helps to advance our understanding of cuttings transport phenomena, providing insights that are applicable under practical drilling scenarios.

Our research was divided into two stages. First, we developed and validated a Computational Fluid Dynamics (CFD) model for an isothermal, laminar, and incompressible multiphase flow. Second, using the validated model, we conducted a comprehensive investigation of the combined effects of the drill string rotation, flow rate, and rate of penetration (ROP) across three inclination angles, with two distinct fluid rheologies, on cuttings transport—an approach rarely explored within a single study. We utilized ANSYS FLUENT (2023-R1) with advanced modeling techniques to simulate a solid–liquid multiphase flow within an annulus, achieving high accuracy with only a 4.24% error compared to the experimental data.

2. Literature Review

Numerous studies have been conducted to investigate the transportation of drilled cuttings. Over the past three decades, significant efforts have been made through experiments, modeling, and simulations to understand the transport phenomena and the influencing parameters. Each of these studies focused on certain parameters while simplifying or overlooking others due to the complexities involved.

Researchers have conducted extensive experimental studies using large-scale flow loops with diverse configurations and dimensions to investigate the factors influencing cuttings transport. Zeidler (1972) [6] was among the pioneers in this area, utilizing a 65-foot-long, 8-1/2-inch casing with a 4-1/2-inch drill pipe in a laboratory setup to study the impact of pipe rotation on cuttings transport. Following this, Okranjni and Azar (1985) [7] focused on the effects of field-measured mud rheological properties using a 40-foot-long transparent flow loop section and 15 different mud systems. Tormen et al. (1986) [8] highlighted that deviated wells with angles between 40° and 50° require higher annular velocities for effective hole cleaning, based on their study using the same flow loop as Okranjni and Azar. Peden et al. (1990) [9] found that pipe rotation significantly reduces the minimum transport velocity required in medium-to-highly viscous fluids, which aids cuttings transport in small annuli or with positive eccentricity. Sanchez et al. (1999) [10] employed an 8-inch by 4.5-inch, 100-foot-long wellbore simulator and discovered that at high rotary speeds and with high-viscosity mud, smaller cuttings are more easily transported. Duan et al. (2006) [11], using the same flow loop as Sanchez et al., examined how fluid rheology affects the transport of smaller cuttings. Ozbayoglu et al. (2008) [12] demonstrated through the Middle East Technical University (METU) cuttings transport flow loop that effective hole cleaning can be achieved with a combination of drill string rotation and mud viscosity, even at lower speeds. In a subsequent study using the same flow loop, Osgouei (2010) [13] observed that a higher rate of penetration (ROP) increases the cuttings concentration and annular pressure losses, although increasing the fluid velocity did improve cuttings transport. However, they also noted that drill string rotation had a minimal effect on the cuttings concentration in the horizontal annulus under stable conditions. Han et al. (2010) [14] reported that while drill string rotation generally enhances cuttings transport, particularly at lower flow rates, it also increases annular friction pressure losses with higher fluid velocity, well inclination, and drill string rotation. They further noted that the effect of drill string rotation on cuttings transport was more significant in water compared to non-Newtonian fluids. Ytrehus et al. (2014) [15] explored various flow loop configurations to evaluate the effectiveness of cuttings transport in water-based drilling fluids, finding that the hole cleaning performance varied significantly even among drilling fluids with identical rheological properties and densities according to API standards.

On the other hand, several studies have employed the mechanistic method in transport phenomena, which is based on a phenomenological approach that considers fundamental principles such as the conservation of mass and energy. These models typically adopt either a two-layer or three-layer approach for horizontal or inclined wellbores. The two-layer model consists of a suspended layer and a stationary or mobile cuttings bed, while the three-layer model includes a suspended layer, a stationary cuttings bed, and a mobile cuttings bed. The primary forces considered in these models are drag, lift, gravity, and friction. Notable mechanistic model studies include those by Gravignet and Sobey (1989) [16], who developed a two-layer cuttings transport model to estimate bed thickness based on the flow rate, ROP, and geometry. Martins and Santana (1992) [17] presented a two-layer model that calculated the bed heights, average solids concentration, and frictional losses based on observed flow patterns. Kamp and Rivero (1999) [18] also developed a two-layer model, predicting the bed thickness as a function of various parameters. Hyun et al. (2000) [19] introduced a three-layer model aimed at determining the optimal flow rate and optimizing fluid rheology for three different well inclinations. Ramadan et al. (2003) [20] developed a mechanistic model to predict the critical velocities required to move spherical cuttings beds with varying particle sizes. In 2005 [21], they further created a three-layer model to estimate the annular frictional pressure losses and cuttings transport capacity across different fluid rheologies. Malekzadeh and Mohammadsaleh (2011) [22] developed a model to predict the minimum flow rate required to ensure effective cuttings removal. Wang et al. (2011) [23] introduced a three-layer model to determine the sediment bed thickness in extended reach wells. Haolin et al. (2014) [24] developed a mechanistic model to estimate the critical velocity needed to initiate particle movement in deviated wells.

In recent years, Computational Fluid Dynamics (CFD) have increasingly been employed to simulate cuttings transport under various conditions, providing valuable insights into complex phenomena where traditional measurements may be challenging or unattainable. One of the seminal studies in this area was conducted by Bilgesu et al. (2002) [25], who utilized a multiphase solid–liquid model that incorporated both non-Newtonian power-law fluids and Newtonian fluids, such as water. Their research highlighted the critical role of annular velocity in the effective removal of cuttings from the annulus. In a follow-up study in 2007, Bilgesu et al. [26] employed three-dimensional CFD simulations with a Eulerian-mixture model to delve deeper into cuttings transport dynamics. They found that drill string rotation significantly enhanced the movement of smaller particles. However, they also noted challenges associated with higher well inclinations, such as increased particle accumulation and complex movement dynamics, including rolling and sliding. Mishra (2007) [27] investigated the effects of various fluid properties, cuttings sizes, and operational parameters—such as drill string rotation and eccentricity—using a steady-state Eulerian-mixture model. This study assessed the cuttings transport efficiency across different scenarios. Wang et al. (2009) [28] further examined the role of drill string rotation in optimizing hole cleaning in extended reach wells. They applied a multiphase Eulerian flow model to measure variations in the cuttings bed height at different rotational speeds. Sorgan (2010) [29] developed a CFD model that concluded that the fluid velocity was the most significant parameter influencing the cuttings transport performance in deviated and horizontal wells. Sorgan also emphasized the improvement in cuttings removal associated with drill string rotation. Yilmaz (2012) [30] used Discrete Phase Model (DPM) simulations to track particles within the flow domain, focusing on the velocity profiles of the Herschel–Bulkley fluid flow, cuttings bed height in the stationary layer, and bed movement velocities. This study employed the Shear Stress Transport (SST) k-ω turbulence model and validated CFD simulations against previous experimental data. Ofei et al. (2014) [31] developed a Eulerian–Eulerian multiphase flow model to predict the annular pressure losses and cuttings concentration in eccentric horizontal annular spaces. Their model considered various drilling parameters such as the flow rate, fluid rheology, hydraulic diameter, and drill string rotation. Sun et al. (2014) [32] conducted CFD simulations to explore the impacts of drill pipe rotation on the hole cleaning performance in complex well structures using a Eulerian–Eulerian multiphase model. Finally, K. Dewangan et al. (2016) [33] discussed the effects of several parameters, including the non-Newtonian fluid flow rate, drill string rotation speed, and inlet solid concentration, on hole cleaning, utilizing ANSYS FLUENT software for modeling and analysis.

3. Methodology

Our research was structured into two distinct phases, each targeting specific objectives. In the first phase, we developed a CFD model to simulate the multiphase flow encompassing both liquid and solid phases. We validated this model by comparing its outputs against selected experimental data, characterizing the flow as isothermal, laminar, and incompressible.

The second phase focused on examining the effects of various parameters on the transport of drilling cuttings. These parameters included the drill string rotation, flow rate, rate of penetration, well inclination, and fluid rheology, using the CFD model validated in the first phase.

For this study, we employed ANSYS-Fluent software (2023 R1) alongside other associated tools such as ANSYS Workbench. Workbench was utilized to design the model's geometry and generate an appropriate mesh. ANSYS Fluent, in conjunction with ANSYS pre- and post-processing tools, was used to set initial simulation conditions, solve the complex flow equations, and analyze the outcomes of each simulation configuration.

3.1. Geometry

In the process of setting up the model, the first step involves creating the geometry using Design-Modeler. The geometry is considered as a concentric annulus with a length of 1.8 m, composed of two cylindrical components. The inner cylinder, with a diameter of 0.03 m, represents the drill string which can rotate at a constant angular velocity around its axis. The outer cylinder, with a diameter of 0.044 m, represents the casing (Figure 1).

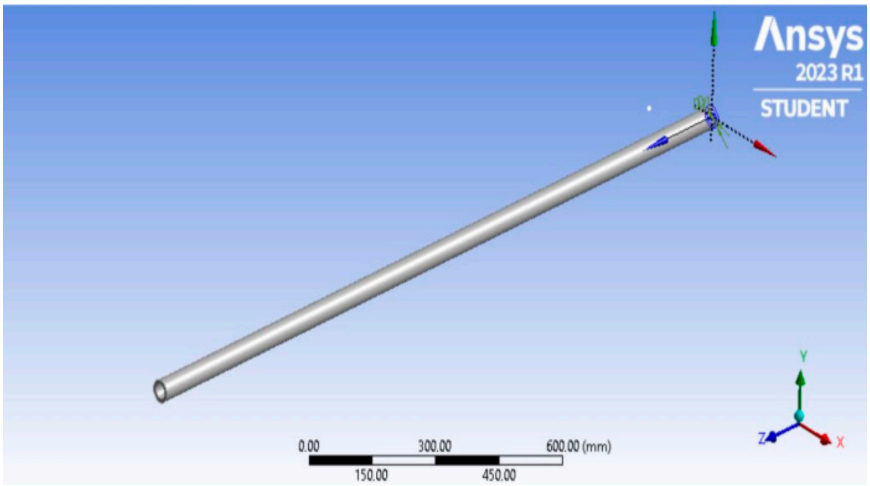

Figure 1. Simulation geometry (D_{inner} = 0.03 m; D_{outer} = 0.044 m; L = 1.8 m).

The length of the annulus and the diameters of the cylinders have been selected based on the parameters used in the experimental study that we used for validation.

3.2. Meshing

Once the geometry has been defined, it is necessary to subdivide it into elements, a process called meshing. The quality of the mesh has a considerable impact on the results obtained in the simulation.

Structured hexahedral meshes have been used for the flow configuration, with a size ranging from 40,000 to 440,000 elements. Edge sizing and face meshing methods have been applied to the inlet and outlet boundaries to ensure good resolution and capture boundary conditions. To ensure an accurate and consistent representation of boundary conditions, the face meshing method was used to divide the inner and outer cylinders into an equal number of divisions (Table 1).

Table 1. Number of elements for each mesh depending on the methods used.

Mesh	Edge Divisions	Radial Face Divisions	Axial Face Divisions
Mesh 1	40	10	100
Mesh 2	60	15	150
Mesh 3	80	20	200
Mesh 4	100	20	220

To determine the optimal mesh resolution for achieving accurate solutions while minimizing computational resources, a mesh independence study was conducted using the meshes listed in Table 1. Flow simulations were performed in an annulus inclined at 60° relative to the vertical, with no drill string rotation, at a fluid velocity of 0.36 m/s. The pressure drop between the inlet and outlet was calculated for each mesh and compared to the experimental result of 1520.32 Pa/m. This comparison facilitated the identification of the optimal mesh resolution needed to balance the accuracy and computational efficiency.

The results of the mesh independence study are summarized in Table 2. The pressure loss results for "Mesh 3" showed a close match with the experimental value of 1520.32 Pa/m, with an error of only 0.77%. This strong alignment confirms that "Mesh 3" offers the optimal configuration for balancing the accuracy and computational efficiency. Figure 2 illustrates the mesh distribution of the selected configuration of "Mesh 3".

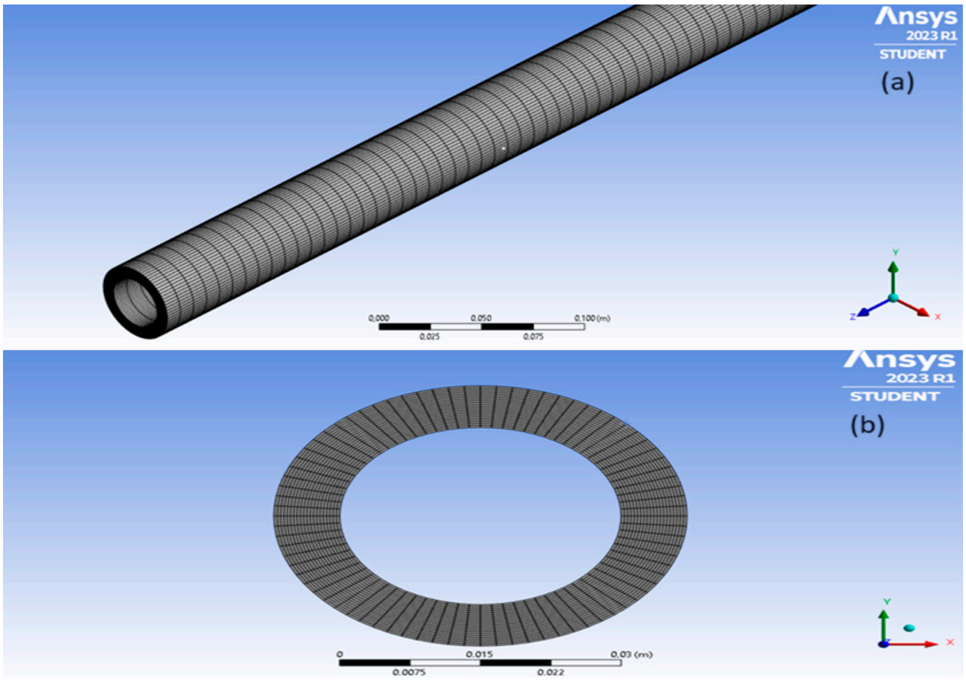

Figure 2. Mesh distribution in the geometry ((**a**) Axial face divisions; (**b**) Edge divisions and Radial face divisions).

Table 2. Results of the mesh independence study.

Mesh	Error (%)
Mesh 1	2.08
Mesh 2	1.26
Mesh 3	0.77
Mesh 4	0.80

3.3. Boundary Conditions

The flow rate of the drilling fluid during operation was modeled by applying a constant velocity at the inlet of the annular domain. The volumetric fraction of the secondary phase was determined based on the equivalent penetration rate. Atmospheric pressure was set as the boundary condition at the outlet. Both the inner and outer drill strings were assumed to be stationary, with no-slip boundary conditions applied to the walls to account for the viscous properties of the carrier fluid. All parameters used in the simulations are detailed in Table 3.

Table 3. Input parameters for simulations based on Han et al.'s experiment [14].

Fluid properties	Fluid type	0.4% CMC (Non-Newtonian)
	Density (kg/m^3)	998.5
	Flow index n	0.75
	Consistency index K (Pa·s^n)	0.048
Particle properties	Cuttings density (kg/m^3)	2550
	Cuttings diameter (m)	0.001
Drilling parameters	ROP (%)	4
	Flow velocities (m/s)	0.36; 0.41; 0.49; 0.57; 0.66
	Flow pattern	Laminar
	Rotation speed (rpm)	0
	Eccentricity	0
	Well inclination (◦)	60

3.3.1. Fluid Flow Rate

The boundary conditions available for the Eulerian multiphase model simulations are limited. In our case, the velocity inlet boundary conditions are used to define the velocity and scalar properties of the flow at the inlet boundaries.

$$v_t = \frac{Q}{A_{ann}} \tag{1}$$

where v_t represents a constant velocity at the inlet, Q represents the flow rate, and A_{ann} represents the annular space surface.

3.3.2. Volume Fraction

The volume fraction of solid particles at the inlet of the flow domain provides an idea of the quantity of cuttings generated during the drilling operation. It is calculated according to the equation [12].

$$c_c = \frac{(ROP)A_{bit}}{R_t Q} \tag{2}$$

where:

- c_c: cuttings concentration.
- ROP: rate of penetration.
- A_{bit}: bit space surface.
- R_t: particle transport velocity ratio.
- Q: flow rate.

3.4. Solver Configuration

The geometry and mesh of the created model are imported into the Fluent solver, a three-dimensional double precision (3 ddp) solver. In the solver used in this study, appropriate material properties are assigned to each phase, and appropriate boundary conditions are specified for all boundary zones.

The finite volume method has been implemented for the discretization of flow equations in the ANSYS-Fluent solver. The use of this technique ensures the conservation of mass and momentum at the elemental control volume and at the overall level of the geometry, making it physically coherent and, therefore, more suitable in this case.

The pressure–velocity coupling was performed using the "Phase Coupled SIMPLE" scheme. The "Least Squares Cell-Based Method" was used for the gradient, PRESTO! for pressure, and the "First Order Upwind" method for the momentum and volume fraction in spatial discretization properties. The use of a constant time step of 10^{-3} allowed convergence to 10^{-3}. The simulations were performed on a 64-bit computer with 8 GB of RAM and a dual-core processor of 2.7 GHz.

3.5. Model Validation

The results obtained from the developed model were compared to the experimental data from Han et al. (2010) [14]. The comparisons focused on pressure loss, which showed an average error of 4.42%. This value was obtained by calculating the average error across five iterations.

The comparison between the pressure loss results obtained from the numerical model and experimental measurements (Table 4) demonstrates good agreement, as illustrated in Figure 3. The error percentages range from 0.77% to 2.05% for different fluid velocities in the range of 0.36 to 0.57. However, at a velocity of 0.66, a significant error of 14.73% is observed between the numerical and experimental results. This discrepancy suggests that the increased velocity may introduce instability in the numerical simulations, potentially impacting the accuracy of the results. This is particularly relevant as the simulations are conducted under laminar flow conditions within a specific velocity range.

Table 4. Error between simulation and experimental results.

Fluid Velocity (m/s)	Experimental Pressure Loss (Pa/m)	Simulation Pressure Loss (Pa/m)	Error (%)
0.36	1520.32	1532.18	0.77
0.41	1708.55	1733.01	1.43
0.49	1996.30	2059.01	3.14
0.57	2157.32	2201.7	2.05
0.66	2424.42	2781.67	14.73

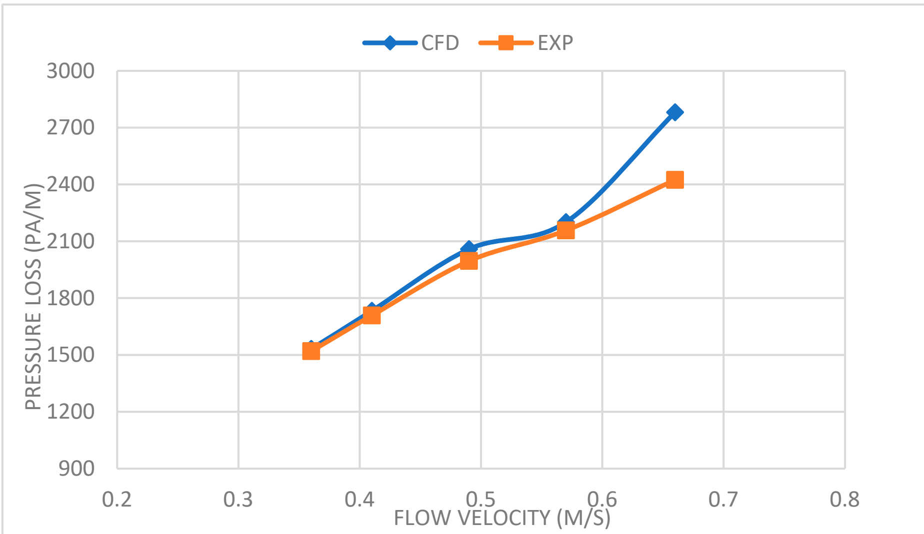

Figure 3. Comparison between simulation results and experimental data.

3.6. Sensitivity Analysis

Using the already developed and validated CFD model, we conducted a comprehensive analysis of the impact of several parameters on the transport of cuttings. These parameters include the drill string rotation, flow rate, rate of penetration, inclination, and rheology.

This analysis was performed considering three inclination configurations and using two fluids with distinct rheological characteristics (different density and viscosity). We began by studying the effect of a varying drill string rotation, flow rate, and rate of penetration on the cuttings concentration and pressure loss. Then, we focused on the impact of inclination and rheology on the particles' (cuttings') velocity.

3.6.1. Fluid Properties

The drilling fluids used in this study are non-Newtonian fluids following the power law model. They consist of mixtures containing 350 mL of water, 22.5 g of bentonite, and 2 g and 2.5 g of XG (xanthan gum) for "Fluid 1" and "Fluid 2", respectively. The properties of the fluids were obtained from the work of Al-Kayiem et al. (2010) [34], as indicated in Table 5.

Table 5. Fluids properties.

Fluids	**Flow Index n**	**Consistency Index K (Pa·s^n)**	**Density (kg/m^3)**
Fluid 1	0.135	21.29	1042.5
Fluid 2	0.151	22.52	1036.5

3.6.2. Boundary Conditions

The flow rate of the drilling fluid during the drilling operation was modeled by a constant velocity at the inlet using Equation (1). Additionally, the volumetric fraction of the secondary phase was defined based on the equivalent penetration rate (Equation (2)). The atmospheric pressure was chosen as the boundary condition at the outlet. The inner drill string was considered to be rotating at different angular velocities, while the outer drill string was assumed to be static. Furthermore, no-slip conditions were applied to the walls since the carrier fluid was viscous. All parameters used in the simulations are detailed in Table 6.

Table 6. Input parameters for simulations in the CFD model.

Fluid properties	Fluid type	2; 2.5 XG (Non-Newtonian)
	Density (kg/m^3)	1042.5; 1036.5
	Flow index n	0.135; 0.151
	Consistency index K (Pa·s^n)	21.29; 22.52
Particle properties	Cuttings density (kg/m^3)	2550
	Cuttings diameter (m)	0.001
Drilling parameters	ROP (%)	4; 6; 8
	Flow velocities (m/s)	0.36; 0.41; 0.49; 0.57; 0.66
	Flow pattern	Laminar
	Rotation speed (rpm)	0; 50; 100; 150; 200
	Eccentricity	0
	Well inclination (○)	0; 45; 90

4. Results and Discussion

4.1. Effect of Drill String Rotation

In our study on the effect of drill string rotation on the cuttings concentration (Figures 4–6), we observed a significant correlation between increased rotational speeds and a corresponding reduction in the cuttings concentration within the wellbore. Higher rotational speeds led to a marked decrease in the cuttings concentration across all three inclination angles.

This reduction is primarily attributed to the orbital motion of the drill pipe within the annulus, which generates mechanical agitation and enhances the fluid's capacity to lift and transport cuttings toward the surface [10], thereby improving the overall cuttings removal efficiency. We noticed that the horizontal section exhibited the highest concentration of cuttings compared to other inclinations. This observation underscores that even with similar rotational speeds, cleaning the wellbore in the horizontal section may be more challenging, leading to a more significant accumulation of cuttings.

In comparing the fluids, we observed that the second fluid exhibits a lower cuttings concentration than the first fluid across all segments, as shown in Figures 4–6. This can be attributed to the higher viscosity of fluid 2 compared to fluid 1 [34]. While viscosity enhances particle transportation within a certain range, its effectiveness does not continuously improve with the increasing viscosity [14]. This is particularly evident in the 45°-inclined section (see Figure 5), where, at rotation speeds exceeding 150 rpm, fluid 1 proves more effective at reducing the cuttings concentration compared to fluid 2. For the second fluid, a rotation speed of 100 rpm in the horizontal section results in a minimal cutting concentration (see Figure 6). This indicates that this specific rotation speed is especially effective in reducing cuttings accumulation in the wellbore.

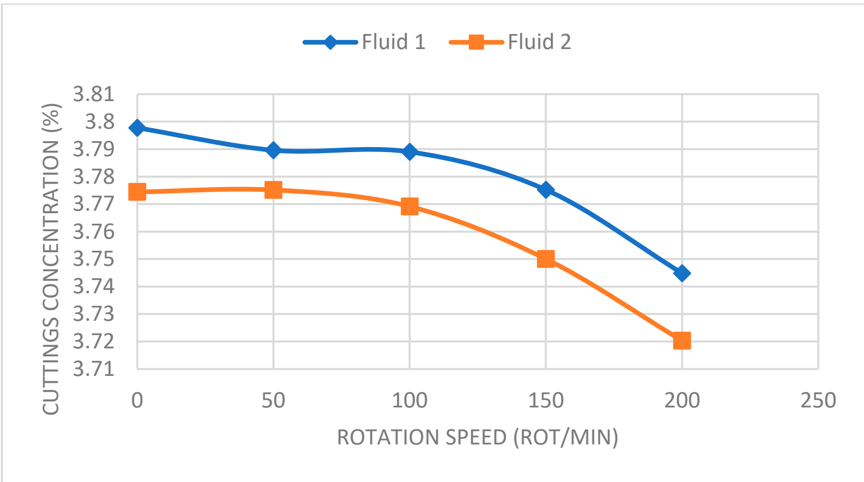

Figure 4. Effect of drill string rotation on cuttings concentration at 0°.

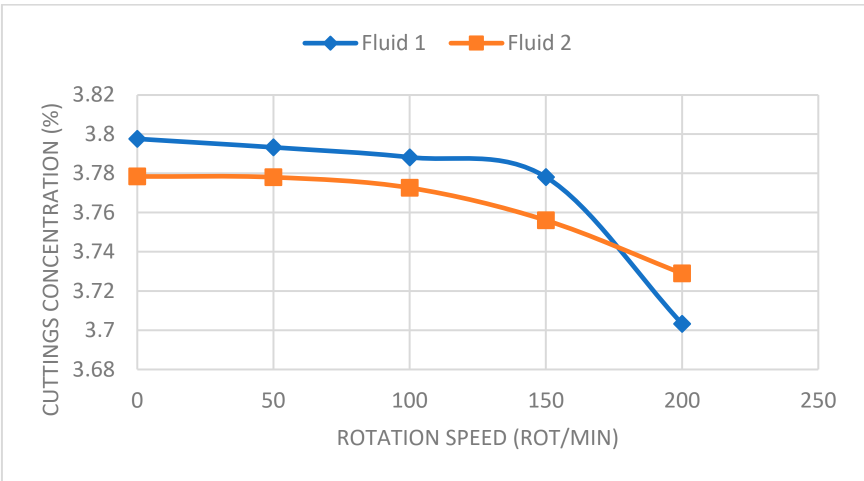

Figure 5. Effect of drill string rotation on cuttings concentration at 45°.

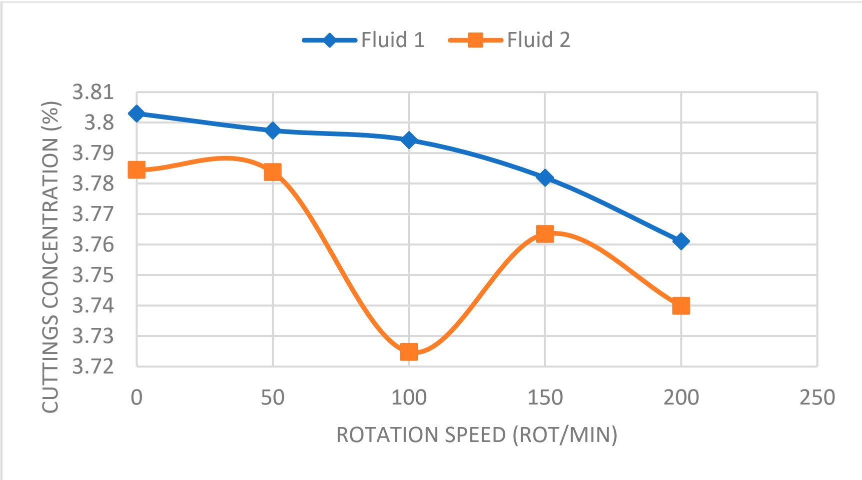

Figure 6. Effect of drill string rotation on cuttings concentration at 90°.

This study also examined the effect of drill string rotation on pressure loss and found that it decreases as the drill string rotation speed increases for both rheologies and all three inclinations at a flow rate of 0.66 m/s. This reduction is induced by the shear thinning effect of power law fluids. The shear thinning phenomenon in non-Newtonian flows tends to reduce pressure loss due to the coupling of axial and rotational flows by the apparent viscosity function dependent on the shear rate. Figures 7–9 clearly illustrate this decrease in pressure loss as the drill string rotation speed increases. It is important to note that a significant difference was observed in the pressure loss values between fluid 1 and fluid 2. For example, in the horizontal section (see Figure 9), at a zero rotation speed, fluid 1 recorded a pressure loss of 23,207 Pa/m, while fluid 2 exhibited a higher pressure loss, reaching 25,747.7 Pa/m. This difference can be attributed to the higher viscosity of fluid 2 compared to fluid 1.

4.2. Effect of Flow Velocity

The simulation results depicted in Figures 10–12 demonstrate the impact of varying fluid flow velocities under laminar conditions on the cuttings concentration across three wellbore inclinations (0°, 45°, and 90°) and two distinct fluid rheologies. When the drill string is stationary, with a Rate of Penetration (ROP) set at 4%, an increase in the flow velocity consistently leads to a reduction in the cuttings concentration, regardless of the wellbore inclination or the fluid's rheological properties. This observation suggests that higher flow velocities generally enhance the efficiency of cuttings removal. However, it is important to note that the cuttings concentration is influenced by both the wellbore inclination and the fluid's rheology. Horizontal wellbores typically exhibit higher cuttings concentrations compared to those inclined at 45° or vertical wells. This indicates that maintaining a low cuttings concentration in horizontal wells may be more challenging, even at similar flow velocities, due to the tendency of cuttings to settle on the low side of the wellbore.

Furthermore, across all three inclinations, when the flow velocity reaches or exceeds 0.41 m/s, the second fluid consistently shows a lower cuttings concentration than the first fluid. This finding suggests that, under these specific conditions, the second fluid, likely due to its higher viscosity, as previously mentioned, is more effective in reducing the cuttings concentration. This highlights its potential advantages for improving cuttings transport in directional drilling operations.

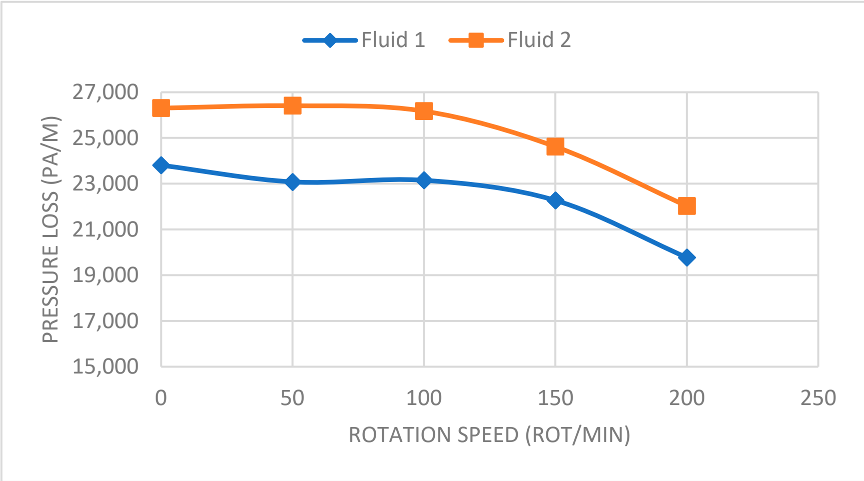

Figure 7. Effect of drill string rotation on pressure loss at 0°.

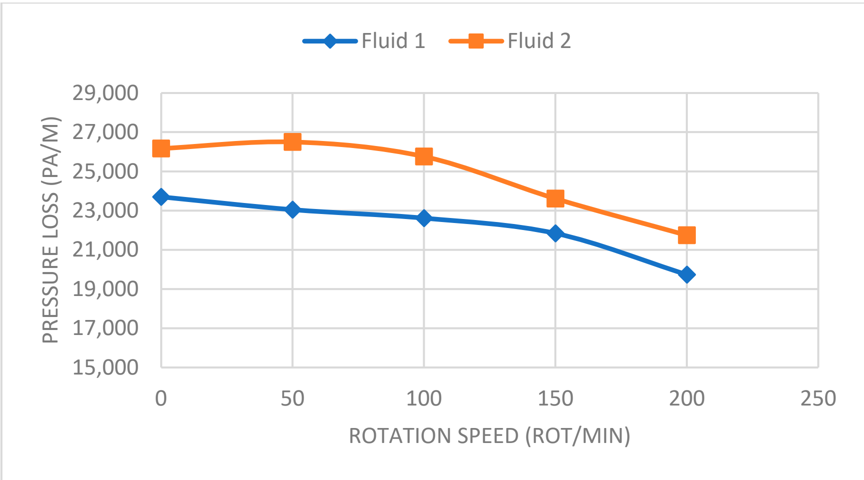

Figure 8. Effect of drill string rotation on pressure loss at 45°.

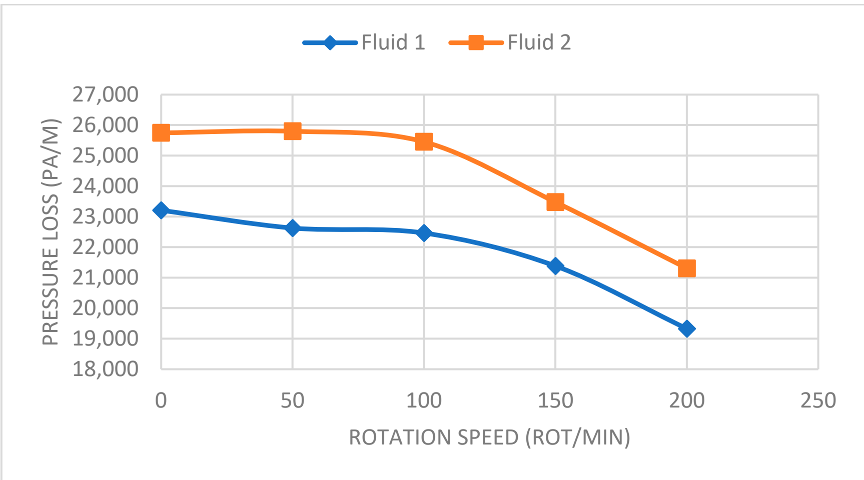

Figure 9. Effect of drill string rotation on pressure loss at 90°.

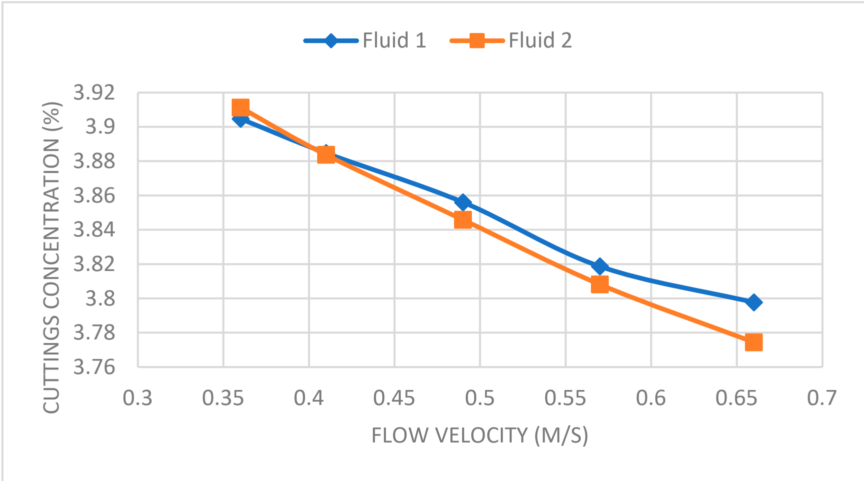

Figure 10. Effect of flow velocity on cuttings concentration at 0°.

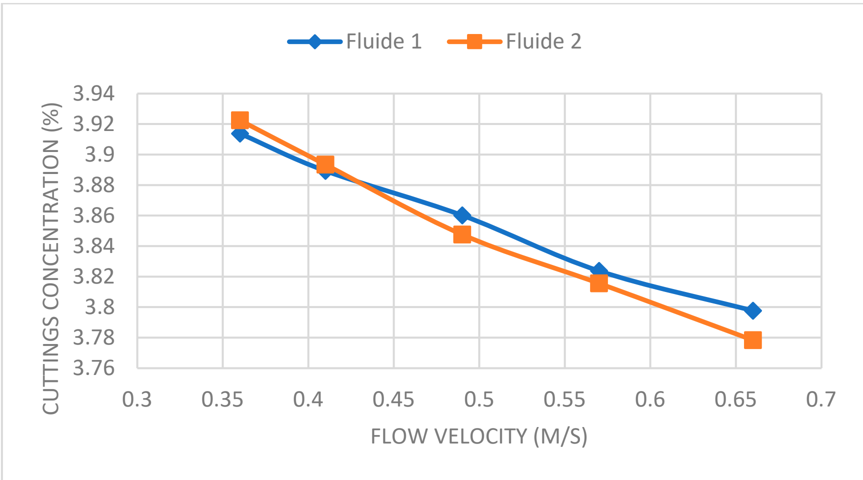

Figure 11. Effect of flow velocity on cuttings concentration at 45°.

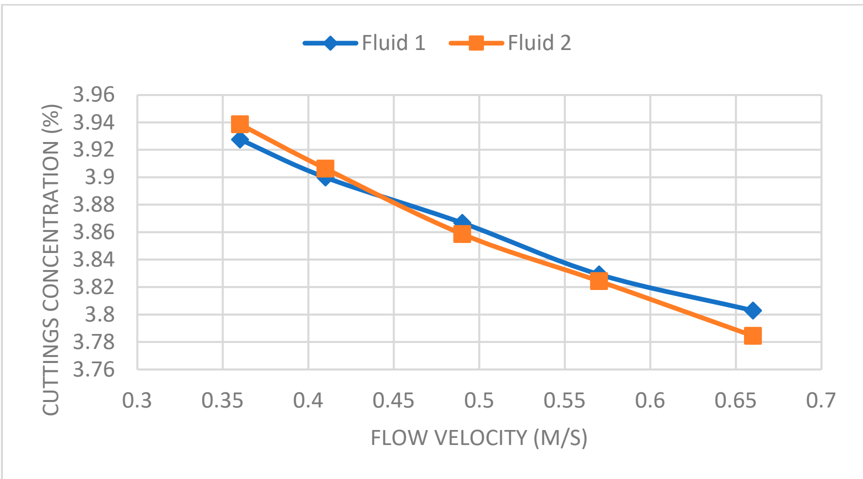

Figure 12. Effect of flow velocity on cuttings concentration at 90°.

As illustrated in Figures 13–15, an increase in the fluid velocity results in a marked rise in pressure loss across all three wellbore segments for both fluid rheologies analyzed. This rise is primarily driven by the drag force exerted by the fluid on the cuttings, combined with increased frictional effects. The elevated pressure loss also contributes to a higher Equivalent Circulating Density (ECD), which could potentially compromise the wellbore stability. Conversely, a reduction in the fluid velocity, as demonstrated earlier in Figures 10–12, leads to an increase in the cuttings concentration. This delicate balance underscores the necessity of carefully optimizing drilling parameters to achieve effective hole cleaning. Adjustments to key factors, such as the flow velocity and fluid density, are essential to maintaining manageable annular pressure losses while minimizing the cuttings concentration.

Additionally, it is important to highlight that the first fluid exhibits a lower pressure loss compared to the second fluid. This difference is attributable to the distinct properties of the first fluid, including its viscosity, density, and enhanced capacity for cuttings transport.

4.3. Effect of Rate of Penetration

The simulation results reveal a clear relationship between the Rate of Penetration (ROP) and the concentration of cuttings in the wellbore. As the ROP increases, the cuttings concentration rises correspondingly across all three wellbore segments and for both fluids studied, as illustrated in Figures 16–18, with other drilling parameters remaining constant. This increase in cuttings concentration can be attributed to the reduced cross-sectional area available for the fluid flow within the annular geometry as the penetration rate increases, which subsequently leads to higher pressure losses.

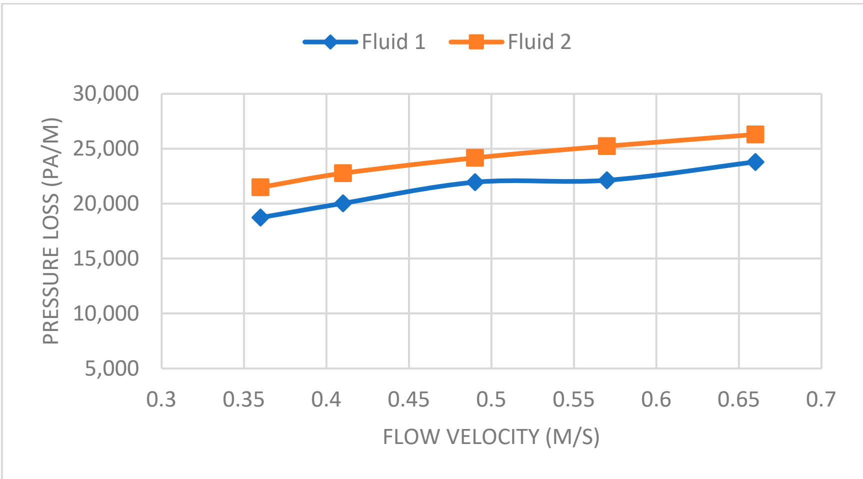

Figure 13. Effect of flow velocity on pressure loss at 0°.

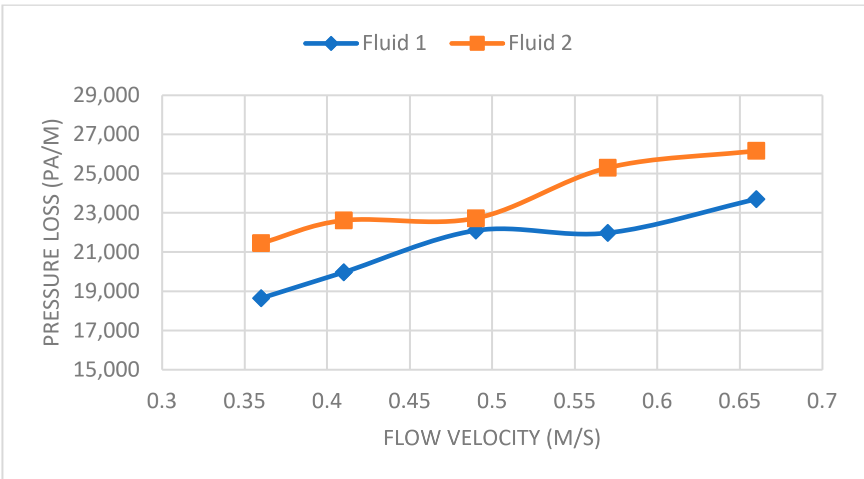

Figure 14. Effect of flow velocity on pressure loss at 45°.

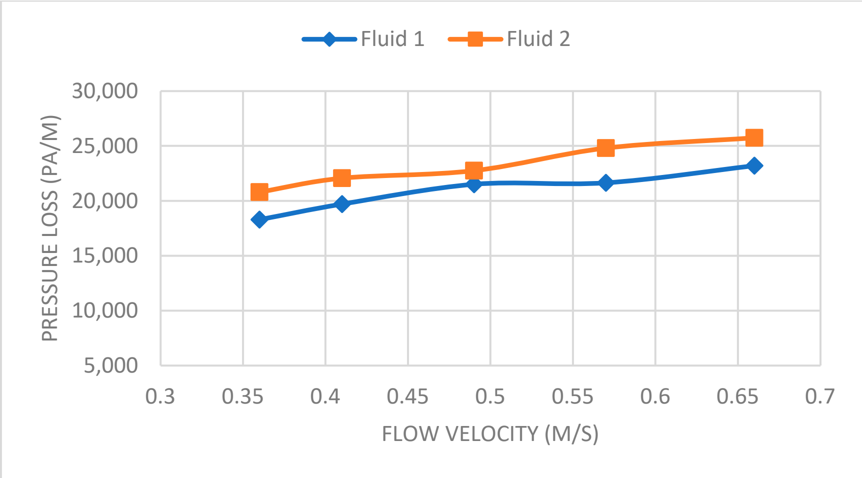

Figure 15. Effect of flow velocity on pressure loss at 90°.

Additionally, it is noteworthy that both fluids exhibit nearly identical cuttings concentration levels across the three wellbore inclinations studied. This suggests that under these specific conditions, both fluids have a similar capacity for cuttings transport. However, the horizontal inclination consistently shows a higher cuttings concentration compared to the other inclinations, indicating greater challenges in achieving efficient cuttings removal in horizontal wellbores.

When examining the impact of pressure losses, it becomes evident that the Rate of Penetration (ROP) has a direct effect, as shown in Figures 19–21. An increase in ROP leads to higher pressure losses, primarily due to the reduced flow area within the annular geometry of the wellbore. Additionally, it is important to note that the second fluid generally exhibits higher pressure losses compared to the first fluid across most sections. However, at a penetration rate of 6 inches in the 45° and 90° sections, the second fluid unexpectedly shows lower pressure losses than the first fluid, as depicted in Figures 20 and 21. This anomaly may indicate unique interactions between the fluid properties and wellbore inclination at higher ROPs, warranting further investigation.

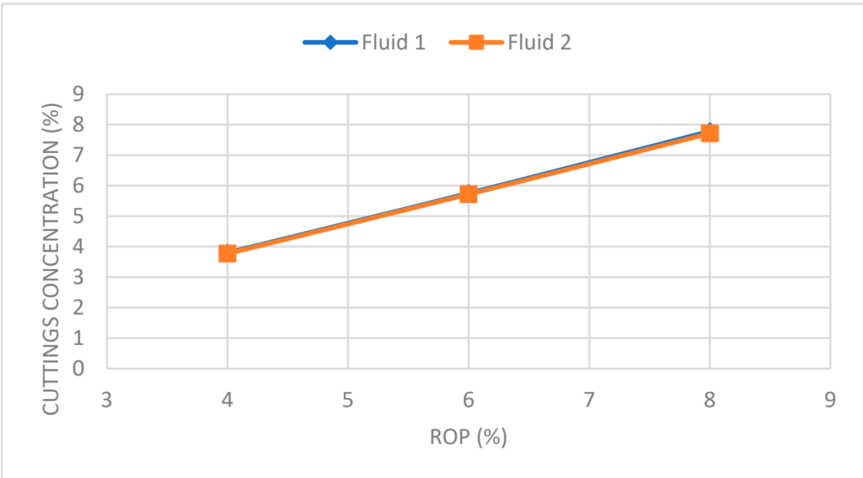

Figure 16. Effect of rate of penetration on cuttings concentration at 0°.

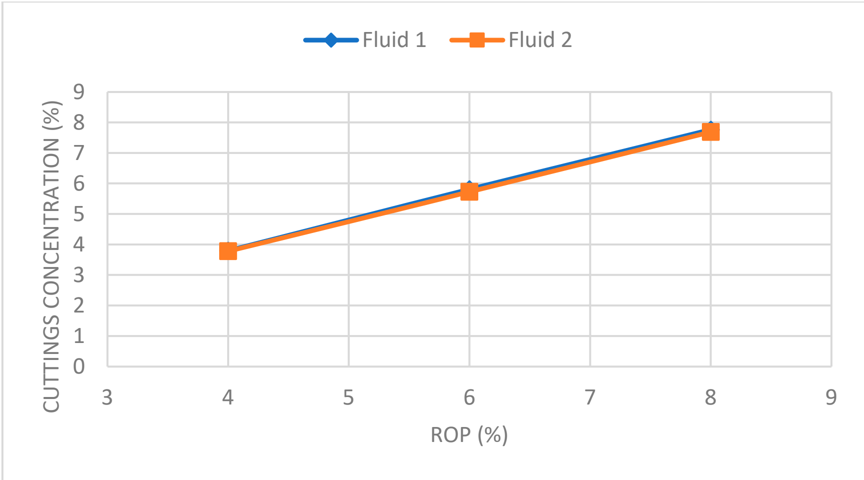

Figure 17. Effect of rate of penetration on cuttings concentration at 45°.

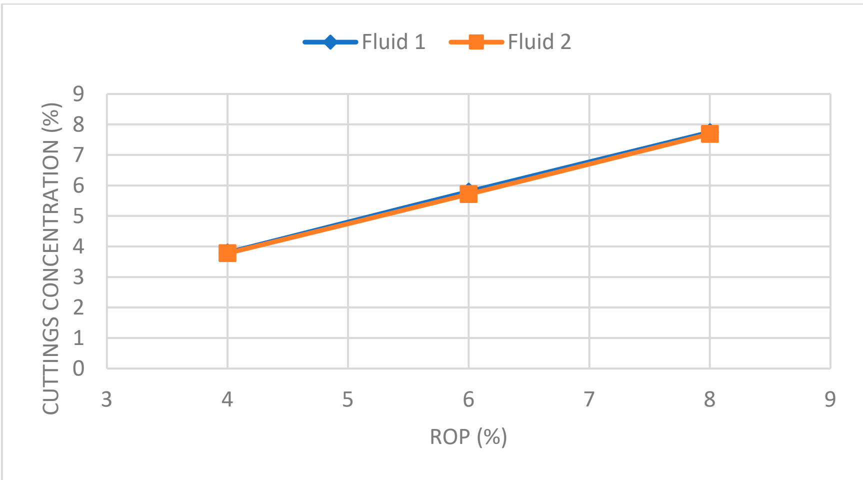

Figure 18. Effect of rate of penetration on cuttings concentration at 90°.

4.4. Effect of Rheology and Inclination on Cuttings Transport Velocity

The figures depict the contours of cuttings outlet velocities in the three segments and the two rheologies at a flow velocity of 0.66 m/s, without any rotation of the drill string and at 4% ROP (Figures 22 and 23). We notice that the cuttings outlet velocity is generally higher in paths offering the least resistance, meaning the paths farthest from the walls of the flow domain. These contours are consistent with the no-slip boundary conditions applied to the walls of the flow domain. We observe that the cuttings outlet velocity increases as the wellbore inclination increases for both rheologies. Additionally, we noticed that the cuttings outlet velocity is higher in the contours of the second fluid compared to the first fluid. For example, let us consider the vertical section: the velocity of the first fluid is 0.7309 m/s while that of the second fluid is 0.7387 m/s, and this trend is also observed in the other sections.

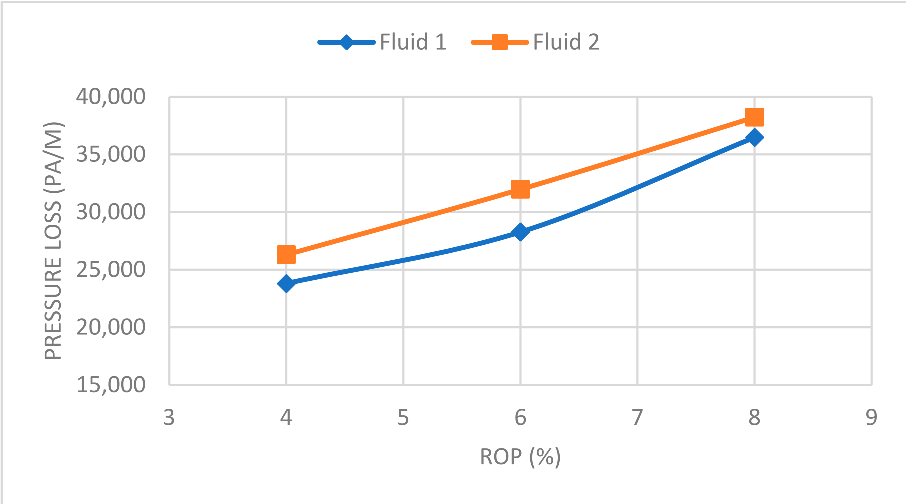

Figure 19. Effect of flow velocity on pressure loss at 0°.

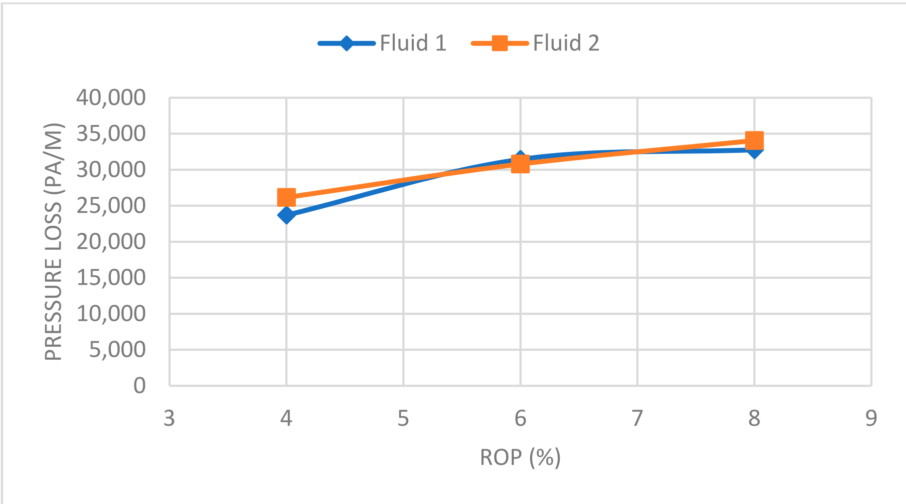

Figure 20. Effect of flow velocity on pressure loss at 45°.

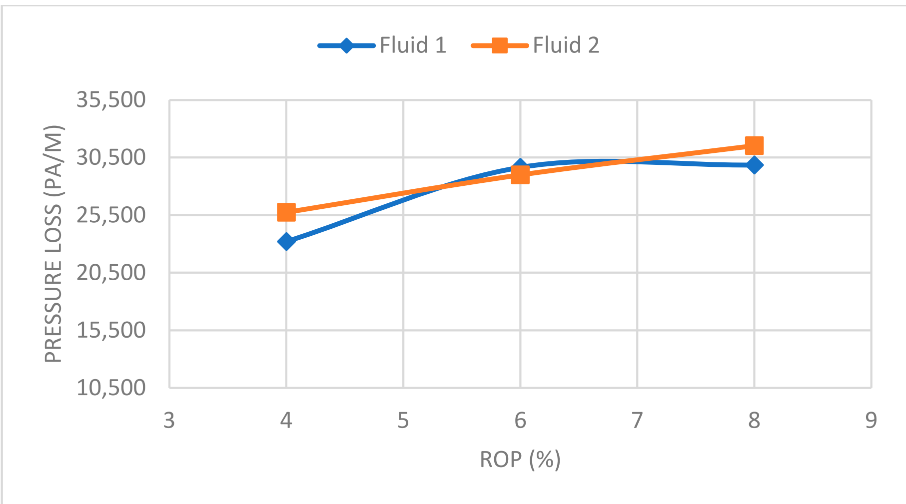

Figure 21. Effect of flow velocity on pressure loss at 90°.

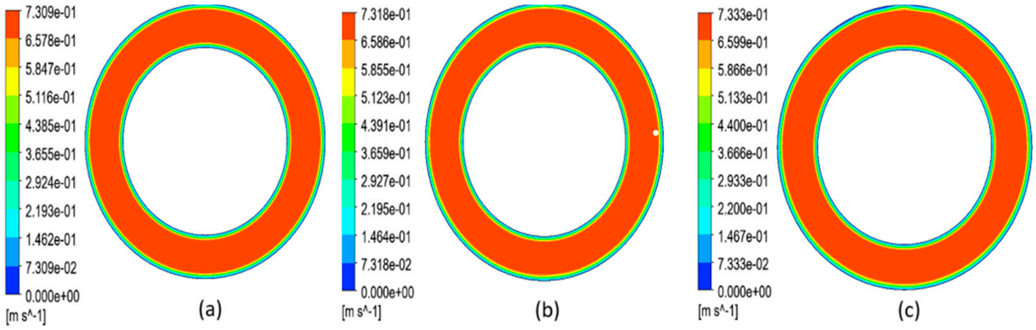

Figure 22. Outlet velocity contours of cuttings for fluid 1 across three segments: (**a**) 0°; (**b**) 45°; (**c**) 90° relative to the vertical.

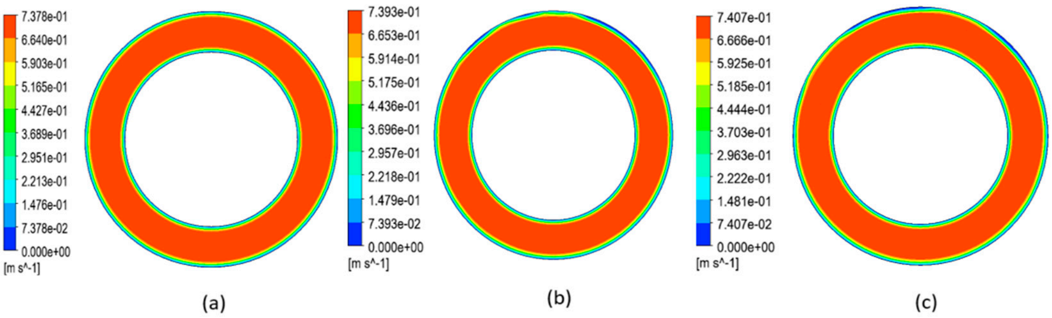

Figure 23. Outlet velocity contours of cuttings for fluid 2 across three segments: (**a**) 0°; (**b**) 45°; (**c**) 90° relative to the vertical.

5. Conclusions

This Computational Fluid Dynamics (CFD) study on wellbore cleaning underlines the complex relationships between drilling parameters and their impact on cuttings transport in oil wells. The research utilized a Euler–Euler multiphase flow model to simulate the effects of the drill string rotation, flow rate, and rate of penetration on the cuttings concentration and pressure loss. With an average error margin of just 4.42% compared to experimental benchmarks, the simulations confirm the model's effectiveness in predicting real-world drilling behaviors. For instance, the reduction in the cuttings concentration was most pronounced at a drill string rotation of 100 RPM, especially in the horizontal sections, pointing to specific operational adjustments that can significantly improve wellbore cleaning.

Additionally, this study reveals the critical influence of fluid rheology and wellbore inclination on cuttings transport. Optimal fluid properties were identified that facilitate the transport and minimize deposition, particularly in wells with high inclination angles where traditional methods are less effective. Adjustments in the flow rate and rheological properties were shown to decrease the cuttings concentration, with an observed reduction in pressure losses by up to 15% under specific conditions. These detailed findings provide actionable insights for drilling engineers to tailor fluid properties and operational parameters, enhancing efficiency and reducing risks associated with complex drilling environments. The study's contributions are thus not only theoretical, but offer a practical framework for improving drilling fluid design and operational strategies in the oil and gas industry.

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