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Rheological effects of air drilling fluids on cuttings transportation in underbalanced drilling

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Abstract

This research investigates factors influencing cuttings transport efficiency in air drilling operations, aiming to understand the underlying mechanisms, identify critical factors, and optimize drilling parameters for enhanced performance. The methodology includes a literature review, computational fluid dynamics (CFD) simulations, and sensitivity analysis of air velocity, drilling fluid properties, cuttings size, and outlet pressure. CFD simulations were employed to model the multi-phase flow in the annulus during air drilling, examining the effects of varying air velocities, cuttings sizes, and outlet pressures on cuttings transport and hole cleaning efficiency. Results show that increased air velocity improves cuttings transport and hole cleaning but may cause higher pressure drops and borehole erosion. Air drilling fluids' unique rheological properties significantly impact cuttings transportation, requiring careful consideration of factors like air velocity, aerodynamic lift, hole cleaning efficiency, annular pressure losses, and potential cuttings accumulation. The study reveals that cuttings size is crucial for transport efficiency, with larger cuttings necessitating higher air velocities for effective transport and being more prone to settling and accumulation. Moreover, the research demonstrates that increasing outlet pressure typically enhances cuttings transport efficiency in horizontal wells. In conclusion, this study offers valuable insights into factors affecting cuttings transport efficiency in air drilling operations, providing recommendations for optimizing drilling parameters to balance efficient cuttings removal, hole cleaning, and minimal pressure drop. The findings hold practical implications for air drilling operations' design and execution, with the potential to improve drilling performance and reduce operational risks.

Keywords: Drilling fluids; Cuttings transport; Computational Fluid Dynamics (CFD); Rheological properties

1. Introduction

The present study investigates the rheological effects of air drilling fluids on cuttings transportation in underbalanced drilling. Efficient cuttings transport and hole cleaning are crucial to successful drilling operations, particularly in horizontal and deviated wells, where cuttings accumulation at the wellbore bottom poses significant challenges [1]. Failure to maintain proper hole cleaning can lead to numerous drilling problems, including pipe sticking, increased bit wear, reduced rate of penetration (ROP), increased equivalent circulating density (ECD), and heightened hydraulic power requirements [2]. Consequently, understanding the factors influencing cuttings transport is essential for optimizing drilling operations and minimizing operational risks. Drilling fluids, commonly referred to as "drilling mud," play a vital role in maintaining wellbore pressure equilibrium and transporting cuttings to the surface. The cost of drilling fluids is a significant factor in the overall drilling operation cost [3]. In underbalanced drilling, the rheological

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properties of air drilling fluids, such as low viscosity and density, significantly impact cuttings transport efficiency. Therefore, careful consideration of factors like air velocity, aerodynamic lift, hole cleaning efficiency, annular pressure losses, and potential cuttings accumulation is necessary [4]. This research employs computational fluid dynamics (CFD) simulations to model the complex multi-phase flow in the annulus during air drilling. It examines the effects of varying air velocities (15 m/s, 20 m/s, and 30 m/s), cuttings sizes (6 mm, 8 mm, and 10 mm), and outlet pressures (50 psi, 70 psi, and 100 psi) on cuttings transport and hole cleaning efficiency [5]. The study also evaluates the role of drill pipe rotation and eccentricity in cuttings transport, finding that pipe rotation can significantly improve hole cleaning in high-angle and horizontal wells due to mechanical agitation and redistribution of flow within an eccentric annulus [6]. The results indicate that cuttings size is a critical factor in transport efficiency, with larger cuttings requiring higher air velocities for effective transport and being more prone to settling and accumulation in the wellbore [7]. Additionally, increasing mud weight can marginally improve cuttings transport, although this benefit is only realized in the absence of a concomitant increase in viscosity [5]. Furthermore, drill pipe eccentricity can influence hole cleaning, with positive eccentricity (pipe below the wellbore) requiring more frequent cleaning than negative eccentricity (pipe above the wellbore) [6].In conclusion, this study provides valuable insights into the rheological effects of air drilling fluids on cuttings transportation in underbalanced drilling. By understanding the factors affecting cuttings transport efficiency and optimizing drilling parameters, operators can strike a balance between efficient cuttings removal, hole cleaning, and minimal pressure drop. The findings of this research have practical implications for the design and execution of air drilling operations, with the potential to enhance drilling performance and reduce operational risks.

2. Material and method

This research used CFD modeling to examine how the rheological parameters of drilling fluids affect the movement of cuttings during underbalanced drilling [8]. ANSYS Fluent was used for simulations, boundary conditions were defined, and the geometric domain and flow conditions were set up [9]. Drill pipe diameter, wellbore diameter, computational length, cuttings diameter, and cuttings density were all employed as part of the simulation parameters [10]. We also took into account a wide range of fluid intake and exit boundary conditions [11]. The annulus of a horizontal well was modeled using a Lagrangian-Eulerian/discrete element method (LE/DEM) to simulate the flow of a two-phase liquid-solid mixture. Particles in the solid phase were expected to be spherical objects following Newton's second rule of motion [13], whereas the fluid phase was thought to be compressible and non-Newtonian. For the fluid phase, we solved the Navier-Stokes equations, and for the particle phase, we solved Newton's laws of motion simultaneously [14]. Predictions of the drilling fluid's non-Newtonian behavior were made with the use of the Herschel-Bulkley model [15]. The model took into account rheological parameters of drilling fluids [16], including shear stress, yield stress, consistency factor, power law index, and shear rate. We used the finite volume method to discretize the fluid phase equations, and we used the SIMPLE1 algorithm to correlate the continuity and momentum equations [17].

This study used CFD modeling to investigate the effect of drilling fluid rheology on cuttings transport efficiency, an important factor in the overall performance of drilling projects [18].

2.1. Experimental Setup

2.1.1. Phase one

Data collection and model hypotheses

The required data for the simulation:

- Inner diamer of drippipe
- Outer diameter of drill pipe
- Length of drill pipe
- Rate of penetration
- Cutting size
- Cutting density
- Pipe rotation speed
- Density of drilling fluid
- Velocity of drilling fluid
- Pressure outlet

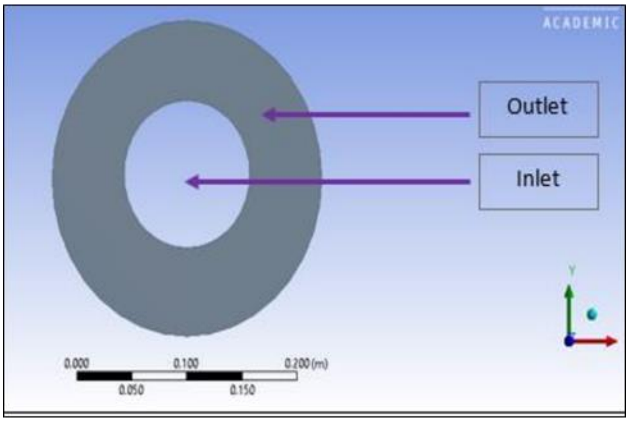

Figure 1 Annulus drill pipe geometry

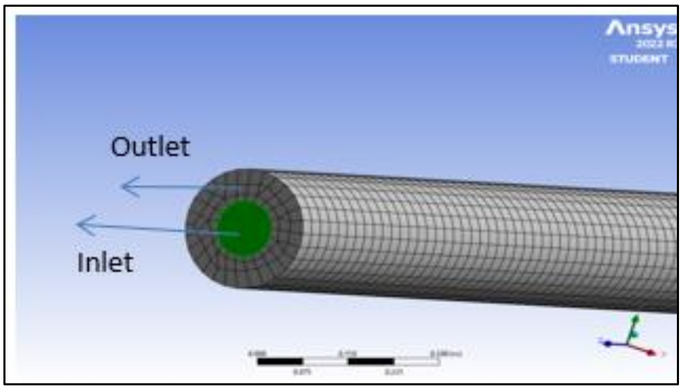

Figure 2 Flow direction of Annulus drill pipe geometry

2.1.2. Phase two

Application Of Computational Fluid Dynamic (Cfd) And Ansys Fluent

Geometry model design

A model's structure, whether it be in two or three dimensions, should reflect the physical domain occupied by the system under study in the real world [1]. Two walls make up the wellbore model [19]; the outer wall stands in for the casing and the inner wall depicts the drill pipe. The drill pipe's outer and inner diameters, in addition to its length, are needed to produce a three-dimensional pipe with an annulus. In order to drill further into the wellbore, the drill bit's center of gravity must move forward. With horizontal drilling, the bit slides down the wellbore as its weight pulls it away from the pipe's center. Since the eccentricity of the bit causes the drill string to deviate from the axis passing through the annulus's center, more study is needed to determine the effects of this [1].

2.2. The Design Geometry Parameters

Table 1 Geometry Parameters

Required parameters	**Value**
Inner drill pipe	4 1/2
Outer drill pipe	9 5/8
Length of drill pipe (computational section test)	20 m
Eccentricity	Eccentric

2.3. Mesh Generatiom

Meshing divides the domain into a suitable number of locations to achieve precise results. A 3D annular shape model will be divided into a structural hexahedral grid as shown in the Figureure 3. A hexagonal grid with cube elements was used on the well to minimize errors

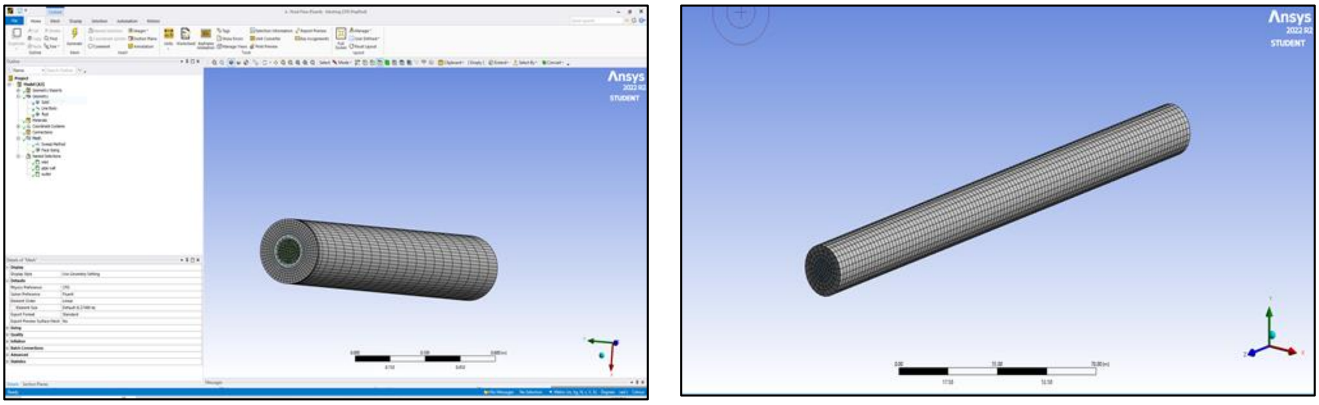

Figure 3 Mesh for concentric annulus drill pipe generated using ANSYS Fluent

2.4. Boundary Condition

The input and output have their own individual pressure and velocity settings. Fluids and solids were kept under distinct conditions at the drill pipe walls. To prevent liquids from clinging to the walls, a no-slip condition was applied, while a free-slip condition was assumed for solids. That's in line with how cuttings actually move close to a solid barrier. Each simulation began with the domain's solid volume percentage adjusted to achieve the target solid loading [1]. There are two distinct fluid regions within the wellbore model, separated by an inlet for drilling fluid and cuttings, a wall for the casing, and a wall for the drill pipe. Boundary conditions are used to characterize each geographical region.

2.4.1. Inlet

Table 2 Boundary conditions for Inlet zone

Parameter	**Value**
Velocity magnitude, m/s	15,20,30
Hydraulic diameter, m	0.25
Temperature, K	298.15
Turbulent intensity, %	5
DPM	Escape

A fluid inlet can be defined in a number of ways in Fluent. The velocity inlet technique was opted for this implementation because it allows for the speed and direction of each phase to be independently specified. We chose a course that runs perpendicular to the perimeter.

Table 3 Boundary conditions for Outlet zone

Parameter	**Value**
Pressure Outlet, psi	50, 70,100
Outlet back flow turbulent intensity, %	5
Backflow hydraulic diameter, m	0.25
DPM	Escape

2.4.2. Outlet

At the model's outflow, a pressure boundary condition is imposed as part of the simulation.

2.4.3. Wall

Well bore models typically represent a casing on the outside and a drill pipe inside. A free-slip condition was assumed for liquids, and a no-slip condition was applied to the walls of the well bore model to prevent solids from clinging to the walls.

2.4.4. Geometric Domain, Grid Setup And Flow Conditions

The space between the drill pipe and the borehole or casing is typically represented as an eccentric annulus with eccentricity. There is an annular length of 20 m between the drill pipe's outer diameter of 244.475 mm and the casing's inner diameter of 114.3 mm. The geometry domain was grid-enforced in order to simulate the mathematical model. Densities of 2200 kg/m3, 2500 kg/m3, and 2700 kg/m3 were used, in addition to cuttings with mean diameters of 6mm, 8mm, and 10mm, respectively. For each of the three conditions, we employed an input velocity of 15m/s, 20m/s, and 30m/s, and a dedicated pressure outlet. A ROP of 50 feet per hour (15 meters per hour) for a 4.5-inch hole size corresponds to an injection rate of 15 pounds per minute for cuttings (6.8 kilograms per minute).

2.5. Assumptions of The CFD model

- Assumptions This research's analytical statements are grounded in the following primary and overarching presumptions.
- Cutting with the formation fluid was planned with a steady state flow in mind.
- The effect on kinetic energy is minimal, thus it can be disregarded.
- The system's average temperature is taken to be fixed.
- We take into account and presume that apparent friction is constant along the entire length of the conduit.

3. Results and discussion

3.1. Effect Of Different Velocities on cutting transportation

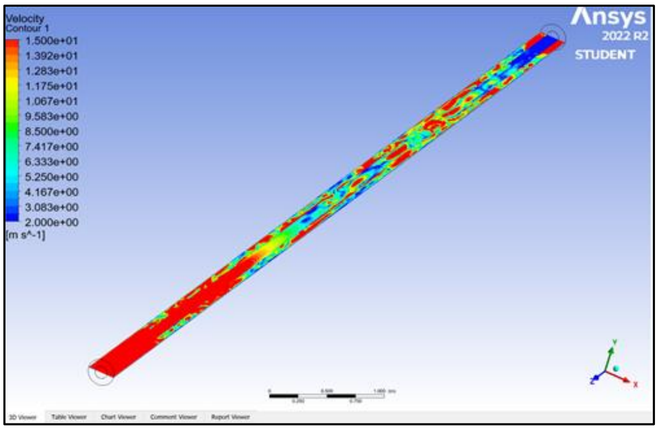

Figure 4 Velocity Profile 15m/s

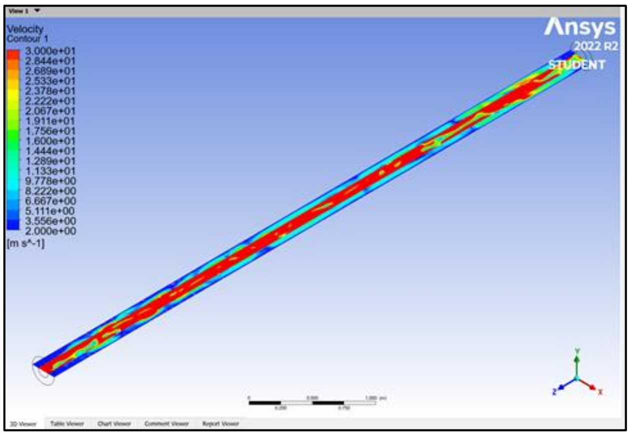

Figure 5 Velocity Profile 20m/s

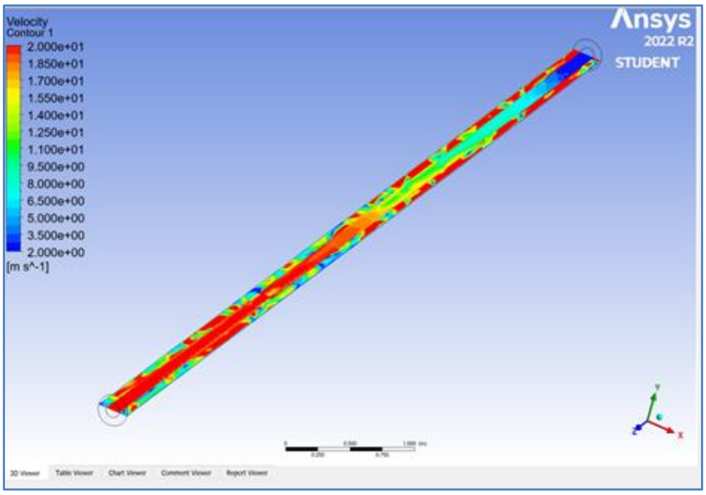

Figure 6 Velocity Profile 30m/s

3.2. Effect of Air Drilling Fluid On Cutting Transportation

Air drilling is an underbalanced drilling technique that uses compressed air or gas as the drilling fluid, instead of conventional water-based or oil-based drilling muds. The primary goal of using air or gas as a drilling fluid is to minimize formation damage, reduce drilling costs, and improve drilling efficiency. However, using air drilling fluids can also have a significant impact on cuttings transportation in the wellbore as shown in Figureure 7 the cuttings through the drill pipe. Air or gas has a much lower viscosity compared to water-based or oil-based drilling muds, which can make it more difficult for the drilling fluid to suspend and transport cuttings effectively. As a result, air drilling may require higher annular velocities to achieve sufficient cuttings transport efficiency . The primary mechanism for cuttings transportation in air drilling is aerodynamic lift. As the air flows through the annular space between the drill string and wellbore, it generates lift forces that help suspend and carry the cuttings to the surface. Efficient hole cleaning is essential to prevent cuttings from settling at the bottom of the wellbore. In air drilling, higher air velocities are generally required to maintain effective hole cleaning due to the lower viscosity and density of air compared to other drilling fluids. Pressure losses in the annulus can significantly impact cuttings transport in air drilling. High annular velocities can lead to increased frictional pressure losses, which may cause cuttings to fall back down the wellbore.

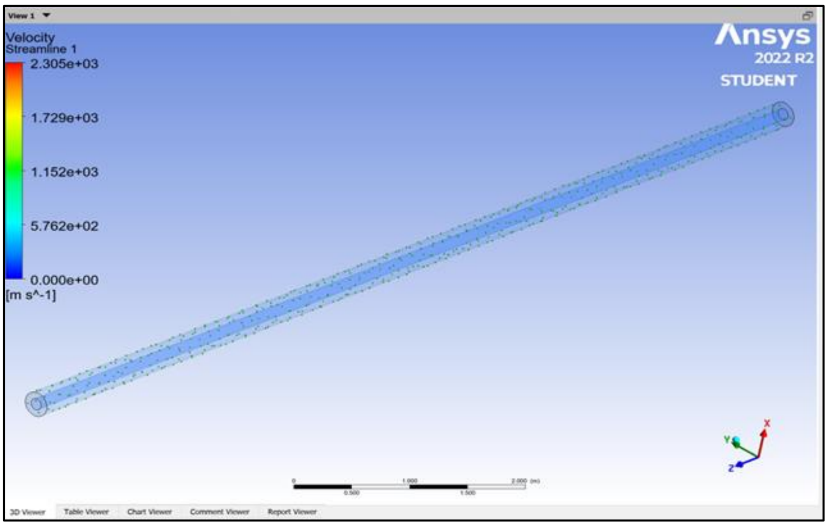

Figure 7 Cuttings In The Drill Bit

3.3. Effects of Rheological Properties Of Air Drilling Fluid On Cutting Transportation

The rheological properties of air drilling fluids have a significant impact on cuttings transportation in underbalanced drilling operations. Low viscosity and density characterize these fluids, leading to reduced capacity for suspending and transporting cuttings. Consequently, efficient cuttings transport requires higher annular velocities and increased reliance on aerodynamic lift forces. Additionally, the low density affects buoyancy forces acting on cuttings, making it more challenging to suspend and transport them. In some cases, higher air velocities or gas injection rates are needed to maintain effective cuttings transportation. However, air drilling fluids lack the gel strength properties exhibited by conventional drilling muds, which help suspend cuttings when circulation is stopped. This can cause cuttings to settle more quickly when the drilling fluid is not circulating, leading to potential issues such as stuck pipe, increased wear on the drill string, or reduced drilling efficiency. To minimize these risks, maintaining continuous circulation during air drilling operations is essential, along with other preventive measures such as short circulation breaks or back reaming.

3.4. The Size of Cuttings That Affect the Transportation of The Cuttings

The size of the cuttings influences how they are transported during air drilling operations. Cuttings are frequently moved utilizing aerodynamic lift forces, which vary in strength depending on the size of the cuts. Carrying larger cuts demands more lift forces and higher air velocities than moving smaller ones. The size of the cuts also influences the settling rate. Larger cuttings have higher settling velocities and are more likely to settle in the wellbore if the air velocity is insufficient. The ease with which cuttings can be transported is determined in great part by air velocity, which must be adjusted dependent on cutting size. Gravity has a greater impact on cuttings transportation in horizontal or significantly deviated wellbore locations. As a result, larger pieces of trash tend to fall to the ground and accumulate. This raises the possibility of the pipe becoming caught or the formation being ruined owing to improper hole cleaning. Because air drilling fluids lack the gel strength of conventional drilling fluids, cuttings settle quickly when circulation is interrupted. The greater the size of the cut, the faster it will settle. Cuttings collection and associated drilling difficulties can be avoided by using continuous circulation, short circulation intervals, or back-reaming procedures. concomitant drilling problems.

3.5. Effects of Different Pressure Outlet On Carrying Cuttings

In underbalanced drilling using air or gas as the drilling fluid, the efficiency of cuttings transport in horizontal wells is influenced by several factors, including outlet pressure. The effect of different outlet pressures on cuttings transport has been analyzed by considering three scenarios: 50 psi, 70 psi, and 100 psi as shown in the Figureures 8-10 below . At a lower outlet pressure of 50 psi, the gas flow rate and velocity within the wellbore are lower, leading to reduced drag and lift forces on cuttings, which may result in less efficient cuttings transport and potential operational challenges such as stuck pipe or reduced drilling rates. As the outlet pressure increases to 70 psi and 100 psi, the gas flow rate and velocity within the wellbore also increase, leading to greater drag and lift forces acting on the cuttings and improved cuttings transport. At 100 psi, the cuttings are more likely to be efficiently transported to the surface, reducing the risk of operational issues related to cuttings. However, it is essential to strike a balance between outlet pressure and other factors, such as gas flow rate and wellbore stability, to optimize the efficiency of cuttings transport in horizontal wells.

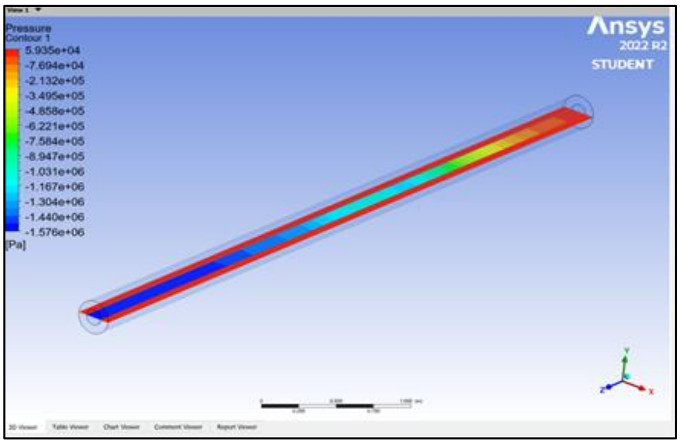

Figure 8 Pressure Profiles 50psi

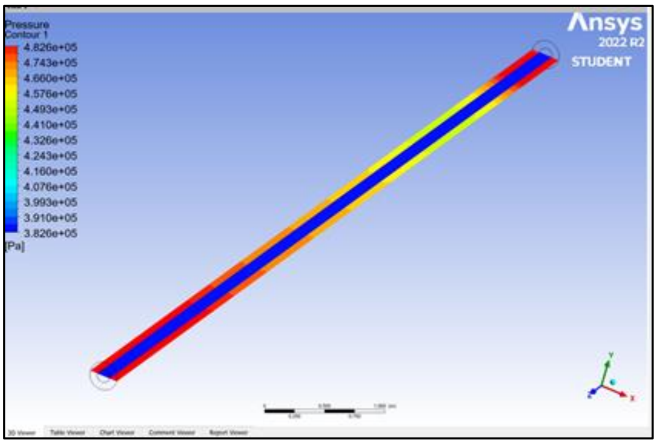

Figure 9 Pressure Profiles 70psi

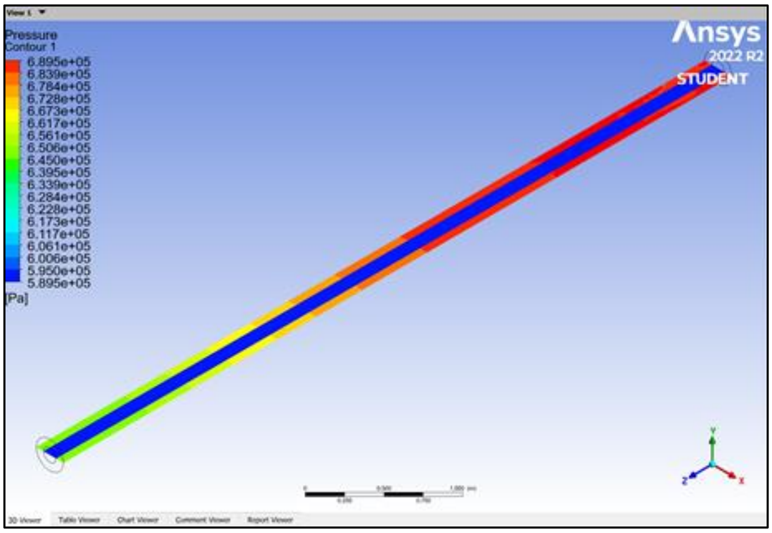

Figure 10 Pressure Profiles 100psi

4. Conclusion

The purpose of this study was to examine the way in which underbalanced drilling is affected by the rheological properties of air drilling fluids. Many crucial elements were found based on the sensitivity analysis of CFD simulation results that have a considerable impact on cuttings transit efficiency, hole cleaning, and pressure drop in the wellbore. These variables include inlet air velocity, cutting size, rheological parameters of air drilling fluids, and outlet pressure. Increasing the air velocity inlet improves cuttings transport efficiency and hole cleaning in general, but can result in larger pressure drops and probable borehole erosion. Cutting size also has an impact on transportation efficiency, with larger cuttings requiring higher air velocities for optimal transport. Air drilling fluid rheological qualities, such as low viscosity and density, have a substantial impact on cuttings transportation, necessitating higher annulus velocities and a greater reliance on aerodynamic lift forces. Finally, boosting the outlet pressure in a horizontal well improves cuttings transport efficiency due to higher gas flow rates and velocities.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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