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COMPUTATIONAL STUDIES TO IMPROVING THE FLOW PHENOMENA OF EXISTING DRILLING FLUID-LINE OPERATIONS

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ABSTRACT

The success of drilling oil and gas wells are highly dependent on the drilling fluid used for drilling and completion. The choice of the drilling fluid and its additives becomes more complex especially when more products of different functions are introduced from time to time. Drilling operations face great technical challenges with drilling problem especially in deep water operation. When exposed to high pressure high temperature (HPHT) conditions, drilling in deep wells will have negative impact on drilling fluids rheological properties. One of the major factors contributing to non-productive time (NPT) in drilling industry is lost circulation, which usually occurs during overbalance drilling operation and is defined as the partial or complete loss of drilling mud into the fracture.

In this study, efforts were made using computational analysis to predict an optimal operations of an existing drilling fluid line systems, the operations has provided valuable insights into both pressure and velocity distribution of the systems. The results reveal significant variations in pressure gradients along the fluid line, with certain regions exhibiting high-pressure zones that may contribute to energy losses and potential wear on the pipeline. Additionally, the velocity distribution analysis highlights areas of uneven flow, including zones of high velocity that could lead to turbulence and inefficiencies, as well as low-velocity regions that may cause sedimentation or blockages.

The results for the 3 predicted fluid samples: water (H_2O), hydrogen peroxide (H_2O_2), and hydrochloric acid (HCl) were validated with the open literature. These findings emphasize the importance of optimizing the fluid line design and operational parameters to improve the overall efficiency and reliability of the system. By addressing pressure and velocity irregularities, the drilling fluid-line can achieve enhanced performance, reduced energy consumption, and extended operational life.

Keywords: CFD; Flow phenomena; Fluid-line, Pipelines, Operations

1.0 INTRODUCTION

Drilling fluid also known as drilling mud is a complex fluid mixture used in drilling operations to facilitate the drilling process and maintain wellbore stability. In most drilling operation, single-phase liquid muds are used as also focused in this research work. Whereas multiphase fluids such as aerated muds may be used in some specific situations (Samaniego et al. 2020). According to drilling experts and field practice, the key to the effective transportability of the drilling fluid lies behind the selection of mud rheological properties Drilling fluid should have adequate rheological properties to prevent the carried cuttings from settling and falling back downhole at low shear rates (Oyeneyin 2021).

Without accurate computational models, drilling operation are been carried out without a full understanding of the complex interaction between drilling fluid and the surrounding environment this can lead to unpredictable and potential dangerous outcomes. Current computational models for drilling fluid flow are inadequate, and this is leading to increased costs and risk associated with drilling operations. The significance of this study is to improve computational models for drilling fluid flow has potential to significantly reduce the risk of accidents and environmental damage caused by drilling operations. By improving the safety and efficiency of drilling operations, the CFD predicted results have positive impact on the production operations of the oil and gas industry as a whole.

2.0 BACKGROUND LITERATURES

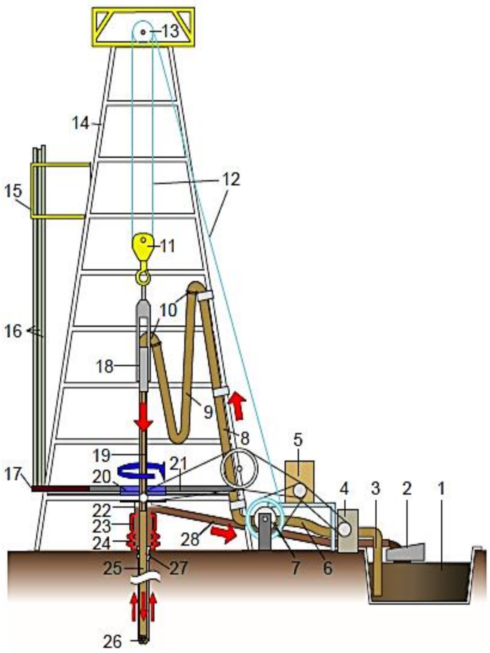
The oil and gas industry plays a pivotal role in the Nigeria's energy landscape and global level at large, providing essential resources for various sectors of society. Within this industry, drilling from the shores and transportation of petroleum products from refineries to distribution points relies heavily on pipeline systems (Idris *et al.,* 2022). The most recent review of the literatures are summarised as presented in Table 1.

Table 1: Summarised version of reviewed investigations

Author(s)	Research Investigations	Research Benefits	Gaps and Remarks
Farshad, 2021	Classification into 3 drilling fluids: (A) oil-based, (B) gas-based and (C) water-based. Oil and gas based drilling fluids pollute the environment due to the use	The use of water-based drilling fluids is recommended.	Environmental issues surrounding the operations

	of fossil fuels.		
Ryen, 2021	Investigate a critical component in the drilling process; It is a carefully designed mixture of various chemicals and materials suspended in a liquid medium.	Played a vital role in ensuring operational success. Optimize drilling performance, ensure wellbore stability, and minimize environmental impact.	No consideration of mal-conditions of operations. An essentials of system-runaway drilling operation

Figure 1 demonstrates a typical drilling fluid rig-line operation, JSTOR 2018. Complete label descriptions of the various components are clearly showed.



1. Mud tank
2. Shale shakers
3. Suction line (mud pump)
4. Mud pump
5. Motor or power source
6. Hose
7. Draw works
8. Standpipe
9. Kelly hose
10. Goose-neck
11. Traveling block
12. Drill line
13. Crown block
14. Derrick
15. Racking Board (Sometimes referred to as the Monkey Board)
16. Stand (of drill pipe)
17. Setback (floor)
18. Swivel (On newer rigs this may be replaced by a top drive)
19. Kelly drive
20. Rotary table
21. Drill floor
22. Bell nipple
23. Blowout preventer (BOP) Annular type
24. Blowout preventer (BOP) Pipe ram & blind ram
25. Drill string
26. Drill bit
27. Casing head or Wellhead
28. Flow line

Fig. 1: Typical component of oil drilling rig plant.
Source: JSTOR, (2018).

Main parameters effect drilling fluid flow: shear stress, pressure drop and pipe rotation. They make controlling on pressure loss in annulus more difficult. But become more respectable when using non- Newtonian fluids such as drilling mud. Pipe rotation drastically decreases frictional pressure loss inside the wellbores. Drilling muds which have viscosity dependent on shear rate, show non-Newtonian behavior. This behavior is complicated to describe with simple models so that the proper selection of rheological model to describe drilling fluid rheology is so important for calculations.(Ahammad, F., Mahmud, S., Zahidul 2019).

2.1 Drilling Fluid Behavior in Drilling Operations

Drilling fluid behavior in drilling operation is a complex phenomenon that plays a crucial role in the efficiency, safety, and cost of the process. The behavior of drilling fluid is influenced by its rheological properties, which include viscosity, plastic viscosity, yield point, gel strength, shear stress, and shear rate. (Adebayo et al. 2022).

During drilling operations, the drilling fluid is subjected to various conditions, including high temperature and high pressures, shear stress and strain, contact with rock formations and cuttings, and chemical reactions with the wellbore and drilling equipment. The drilling fluids behavior in response to these conditions can be categorized into three main phases:

2.1.1 Laminar Flow:

The fluid flows in a smooth, streamlined manner, with minimal resistance. This phase is desirable for efficient drilling and cuttings transport.

2.1.2 Turbulent Flow:

The fluid flows chaotically, with high resistance and energy loss. This phase can lead to reduced drilling efficiency and increased wear on equipment.

2.1.3 Transitional Flow:

The fluid flow in an intermediate regime, exhibiting both laminar and turbulent flow characteristics.

Understanding the behavior of drilling fluid is essential to optimize drilling operations. By controlling the rheological properties and managing the drilling fluid behavior, drilling engineers can improve drilling efficiency and rate of penetration, reduce energy consumption and equipment wear, enhance cuttings transport and wellbore stability, and prevent drilling fluid related problems, such as lost circulation and well control issues.

2.2 Drilling Fluids

2.2.1 Types of Drilling Fluid

Drilling fluids, also known as drilling muds, are complex fluids used in drilling operations to facilitate the drilling process and ensure wellbore stability. The type of drilling fluid used depends on the specific drilling application and the formation being drilled. According to (Bourgoyne et al., 2016), drilling fluids can be broadly classified into three main categories: water-based, oil-based, and synthetic-based muds.

2.2.2 Water-Based Drilling Fluids:

These drilling fluids use water as the continuous phase and are the most commonly used type of drilling fluid. They are cost-effective and relatively environmentally friendly. Water-based drilling fluids are typically used in shallow drilling operations and are effective in soft formations.

2.2.3 Oil-Based Drilling Fluids:

These drilling fluids use oil as the continuous phase and are typically used in deeper drilling operations where high temperatures and pressures are encountered. Oil-based drilling fluids are more expensive than water-based fluids but offer better lubricity and shale inhibition.

2.2.4 Synthetic-Based Drilling Fluids:

These drilling fluids use a mix of oil and synthetic materials as the continuous phase and offer a balance between the properties of water-based and oil based drilling fluids. Synthetic-based drilling fluids are used in operations where oil-based fluids are not suitable due to environmental concerns.

2.3 Fluid Dynamics in Wellbore

Fluid dynamic in a wellbore refers to the behavior of fluids within the wellbore during drilling, production, or injection operations. It is critical aspect of petroleum engineering, as it affects the efficiency, safety, and cost of the operation (Chen et al. 2020).

The fluid dynamic in wellbore includes: Laminar and Turbulent Flow: The flow of fluid in the wellbore can be either laminar (smooth, streamlined) or turbulent (chaotic, unpredictable)

Pressure Drop and Gradient: The pressure drops along the wellbore affects the fluids behavior and must be managed to prevent losses or grains (Wang et al., 2022).

Cuttings Transport: The transport of rock cuttings by the drilling fluid is crucial for efficient drilling and wellbore stability.

Fluid instability and Channeling: Instability and channeling occur due to density difference, leading to reduced efficiency and increased risk (Liu et al., 2019).

2.4 Conditions Subjected to Drilling Fluid during Drilling Operations.

i. Shear stress and strain
ii. Contact with rock formations and cuttings
iii. High temperature and pressures
iv. Chemical reaction with wellbore and drilling equipment

2.5 Cuttings Transport and Hole Cleaning

Cuttings transport is a complex process that involves the movement of rocks cuttings and debris from the wellbore to the surface in drilling operations. The process occurs through a combination of mechanical and hydraulic mechanisms include,

2.5.1 Drilling Fluid Circulation:

Drilling fluid is pumped down the drill pipe and out the bit, where it interacts with the rock cuttings and debris. The fluid then carries the cuttings up the annulus, the space between the drill pipe and the wellbore, to the surface.

Suspension and Transportation:

The drilling fluid suspends the cuttings and transports them up the annulus, where they are removed by solids control equipment.

2.5.2 Erosion and Scouring:

The drilling fluid and cuttings flowing up the annulus can erode and scour the wellbore, helping to remove any remaining cuttings and debris (Al-Mamun et al. 2021).

2.5.3 Hole Cleaning:

Research has focused on developing model and simulations to predict hole cleaning behavior and optimize drilling operations. These efforts aims to improve drilling efficiency, reduce cost, and enhance overall wellbore stability (Zhang et al., 2022). Hole cleaning is a critical aspect of drilling operations that ensures the efficient removal of rocks cuttings and debris from the wellbore. It is a complex process that involves the interaction of various factors, including drilling fluid properties, flow rates wellbore geometry, and rock properties (Liu et al., 2022).

Effective hole cleaning is essential to prevent drilling related problems, such as:

a) Cuttings accumulation and pack off
b) Drilling fluid losses and mud circulation issues
c) Wellbore instability and collapse
d) Reduced drilling efficiency and rate of penetration

2.6 Pressure Losses and Flow Regimes

2.6.1 Pressure Losses

Pressure loss in drilling fluids is a critical aspect of drilling operations, as it affects the drilling efficiency and safety of the drilling process. Pressure loss occurs due to the resistance to flow in the drilling fluid. Pressure loss can be decreased by increasing the pipes rotational speed. Moreover, pressure drop decreased slightly as the drill pipe rotational speed increased, until a critical rotary speed was reached. After this, the pressure drop increased markedly. This trend was the same for all pipe eccentricities at any inclination angles; however, the critical rotational speed at which the pressure loss began to rise was found to depend on both the inclination angle and eccentricity (Mahesh et al., 2022) and categorized pressure loss into three main parts as follows:

1) Frictional Pressure Loss:

This type of pressure loss occurs due to the frictional resistance between the drilling fluid and the pipe or wellbore wall. It is influenced by the fluids viscosity, velocity and roughness of the pipe or wellbore surface.

2) Hydrodynamic Pressure Loss:

This type of pressure loss occurs due to fluids kinetic energy and momentum as it flows through the wellbore. It is influenced by the fluids velocity, density, and the wellbores geometry.

3) Acceleration Pressure Loss:

This type of pressure loss occurs when the fluids velocity changes, such as when it enters a smaller larger pipe or when it encounters a restriction in the wellbore. It is influenced by the fluids density and the magnitude of the velocity change.

2.6.2 Flow Regimes

Flow regimes in drilling fluids refers to the different patterns of fluid flow that occur in the wellbore and pipes during drilling operations. Understanding flow regimes is crucial for optimizing drilling fluid properties, predicting pressure losses, and ensuring efficient and safe drilling operation (Agriandita et al., 2023). There are four main flow regimes in drilling fluids:

1. Laminar Flow:

This regime occurs at low fluid velocities and is characterized by a smooth, continuous flow with minimal turbulence. Laminar flow is typically observed in the annulus (the space between the drill pipe and the wellbore) and is described by the Poisuille equation; the equation was first derived by Jean Louis Marie Poisuille in 1840 and is a fundamental tool in fluid dynamics and pipeline engineering.

Poisuille equation: $\Delta P = \frac{8L\mu v}{\pi R^4}$ (1)

Where: ΔP = pressure drop (Pa), L = length of pipe (m), μ = dynamic viscosity (Pa.s), v = fluid velocity (m/s) and R = pipe radius (m).

2. Turbulent Flow:

This regime occurs at high fluid velocities and is characterized by chaotic, irregular flow with significant turbulence. Turbulent flow is typically observed in the drill pipe and is described by the Prandtl equation.

Prandtl equation: $\Delta P = \frac{fL\rho v}{2D_h}$ (2)

Where: ΔP = pressure drop (Pa), L = length of pipe (m), ρ = fluid density (kg/m^3), v = fluid velocity (m/s) and D_h = hydraulic diameter (m)

3. Annular Flow:

This regime occurs in the annulus and is characterized by a fluid flow with a significant radial component. Annular flow is often observed in deviated wells.

4. Transitional Flow:

This regime occurs at intermediate fluid velocities and is characterized by a mix of laminar and turbulent flow. Transitional flow is often observed in the drill pipe.

2.7 Optimization and Process Modeling of Viscosity of Oil-Based Drilling mud (Oyeneyin, 2021) used bentonite and local clay additives with diesel oil to prepare two drilling muds, with the local clay being beneficiated with hydrochloric acid. The XRF (X-Ray Fluorescence) spectrometer revealed the local clay was mostly silica (SIO2), typical of kaolin. The effects of temperature, aging time, and bentonite clay dosage on the viscosity of each mud were determined using the Response Surface Methodology (RSM) of the design expert software. The RSM revealed the interaction between the three operating variables and their impact in the viscosity of each mud. The optimum viscosities of 19.3 for OBMB (Oil-Based Mud Bentonite) and 25.9 for OBMC (Oil-Based Mud Clay) were obtained at 313K temperature, 30 minutes aging time, and 9wt% bentonite/clay dosage.

2.8 Computational Fluid Dynamics (CFD) in Drilling Fluid Engineering

2.8.1 CFD Software and Validation

Computational fluid dynamics (or CFD) is a robust and powerful tool, highly accurate codes that is used in the analysis of many systems. These systems are which that involves flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation and or modelling. The CFD technique is very robust and cut-across a wide range of industrial and non-industrial application areas (Idris 2014). The ANSYS CFD was formed from two different existed companies in the early 90's (they are the Fluent Inc. and ANS ANSYS CFX Company both in the United States). In 2010, they conclude the arrangement of merger as one and indivisible firm, who can guarantee a highly advance scale in the simulation software that are acceptable worldwide, and the name becomes ANSYS CFD. Since after the merging, the role the ANSYS CFD has been playing is very remarkable to the development of science and engineering worldwide (Idris, 2012).

In drilling fluid operations, CFD simulations can be used to model the behavior of drilling fluids under various operating conditions, such as different flow rates, temperatures, and pressures. This allows drilling engineers to design optimal drilling fluid recipes for specific well conditions and predict fluid behavior under various operating conditions. According to (Al-Mutawa, 2020), CFD modeling of drilling fluids can help to improve drilling efficiency and safety by optimizing drilling fluid design and performance. (Singh, 2018) also notes that CFD can be used to predict and mitigate drilling fluid-related issues, such as fluid loss and well control problems.

3.0 MATERIALS AND METHODS

3.1 Research Materials

A commercial ANSYS licence software student version 2024 was used. The detail corrosive fluids used are depicted in Table 2.

Table 2: Corrosive Fluids used

S/N	Fluids
1	Water
2	Hydrochloric acid
3	Hydrogen peroxide

Table 3: Density of Fluids

S/N	Fluids	Fluid Label	Density (kg/m^3)
1	Water (H_2O)	A	1000
2	Hydrochloric Acid (HCl)	B	1200
3	Hydrogen peroxide (H_2O_2)	C	1100

3.2 Research Methodology

3.2.1 Experimental setup and procedure

Table 4: Specifications of pipe used

Zone	**Parameters**	**Values**
Geometry	Drill pipe diameter, d	0.15
	Pipe length, L	10
	Pipe material	Steel
	Pipe thickness, t (m)	0.005

3.3.1 Pipeline Structure and Drilling Flow

The pipeline structure used in the drilling process was a straight pipe designed to transport fluids such as drilling mud and corrosive substances, including H_2O, H_2O_2, and HCl, under high-pressure and high-temperature conditions. Steel was selected as the material for the pipeline due to its durability, strength, and ability to resist mechanical stresses during operation. The simple, straight design of the pipe eliminated complexities such as bends, valves, or other additional features, focusing solely on the flow dynamics within a linear system.

The drilling flow referred to the movement of these fluids within the straight pipe, which played a crucial role in the efficiency and safety of the drilling process. These fluids served multiple purposes, including cooling and lubricating the drill bit, transporting cuttings to the surface, maintaining wellbore stability, and providing hydraulic power for downhole tools. The fluids exhibited non-Newtonian behaviour, with their viscosity changing depending on the shear rate, and their flow characteristics were influenced by the operational parameters of the pipeline. The interaction between the straight pipe structure and the drilling flow was essential in maintaining optimal performance. The absence of bends or valves simplified the flow patterns, reducing potential areas of turbulence or flow disruptions.

The methodological approach was detailed to encompassing both qualitative and quantitative methods. Qualitative methods are the literature backgrounds and expert consultations, provide foundational insights, while quantitative methods including data analysis and risk modeling, offer a detailed examination of the Maiduguri Depot Plant's pipeline system.

3.3.2 Sequential Steps for Modeling and Simulating Pipe Flow Using CFD Techniques

The study utilizes the ANSYS software as its design tool. ANSYS is versatile engineering analysis software known for predicting a broad spectrum of analyses, including finite element analysis, structural analysis, computational fluid dynamics, explicit and implicit methods, and heat transfer. Recognized as a well-established and user-friendly tool, ANSYS has been effectively employed in solving various engineering problems. This advanced technology enables faster, more accurate and efficient simulations (Idris et al., 2014). This methodology not only captures the physical and operational characteristics of the system but also provides a detailed analysis of the flow behaviour under various conditions. By adhering to these steps, researchers and engineers can identify key factors influencing performance, optimize designs, and predict outcomes with precision. The process consists of five key stages: geometry, mesh, setup, solution, and result analysis.

The geometry of the pipe was modelled as a straight structure without bends or additional features, accurately representing the physical domain for the simulation. A computational mesh was generated to discretize the geometry, with refinement near the walls to capture boundary layer effects and maintain the uniformity required for stable and accurate results. Boundary and initial conditions were applied during the setup phase, including specified inlet velocity, outlet pressure, and no-slip conditions at the walls, along with the selection of a suitable turbulence model for the flow. The solution was obtained by executing the CFD solver while monitoring convergence through residuals and key flow parameters, making necessary adjustments to achieve stability. Finally, the results were analysed using visualizations like velocity contours and pressure distributions, alongside quantitative data such as pressure drop and velocity profiles, providing insights into the flow dynamics within the pipe.

4.0 RESULTS AND DISCUSSIONS

4.1 Simulation Results

The pipe geometry was designed using ANSYS Workbench Vista CPD, while ANSYS CFX was utilized to simulate the flow. A hybrid initialization method was applied to perform the simulation and obtain the desired CFD results. The key outcome of the simulation generates pressure contours and velocity vectors as fundamental predictions. The software provided the results after the analysis were completed and the simulation reached convergence.

In this experiment, various corrosive liquids, such as water (H_2O), hydrogen peroxide (H_2O_2), and hydrochloric acid (HCl) were the selected choice for flow simulation at a rotational speed

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of 3600 revolution per minute (rpm). The CFD post-processing program was used to analyze the simulation results. The initial results obtained for different corrosive fluids are summarized in Figures 2 – 3.

4.1.1 Pipe designed and specification

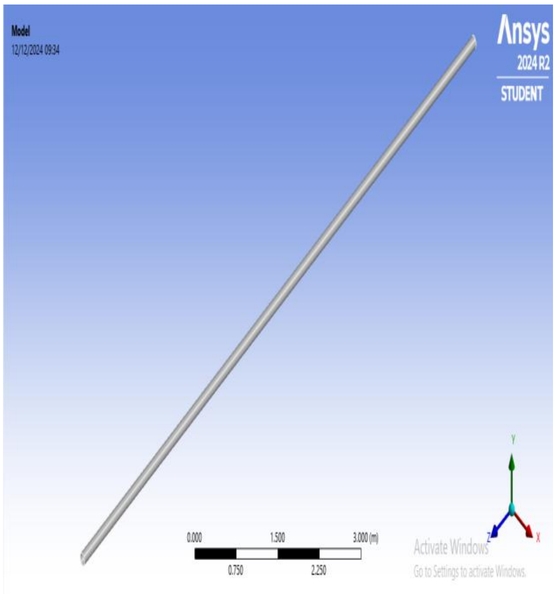

Fig. 2: Pipe Model

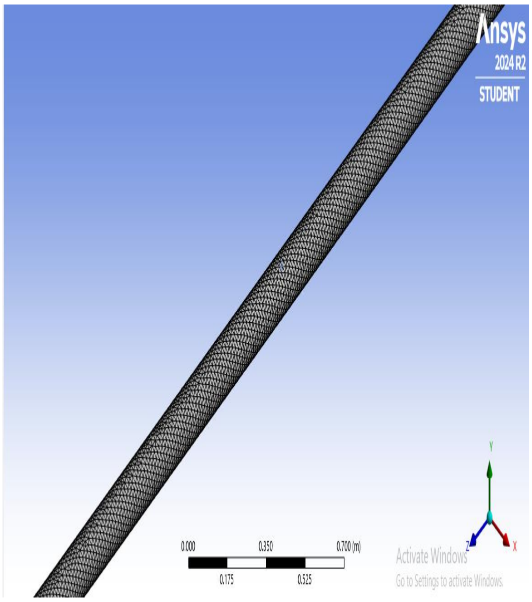

Fig. 3: Pipe Meshed Model

4.1.2 Details of mesh

Table 5: Mesh statistics

S/N	Parameters	Values
1	Nodes	75024
2	Element	56612

4.1.3 Mesh sizing

Table 6: Mesh statistics

S/N	Variables	Values	Units
1	Bounding Box Dia.	10.001	m
2	Average surface	1.6952	m^2
3	Minimum edge length	0.32358	m

4.1.4 Mesh quality

Table 7: Mesh independency analysis

S/N	Parameters	Specification
1	Smoothing	Medium
2	Mesh metric	Skewness

4.1.5 Pressure across the corrosive fluid: A, B and C.

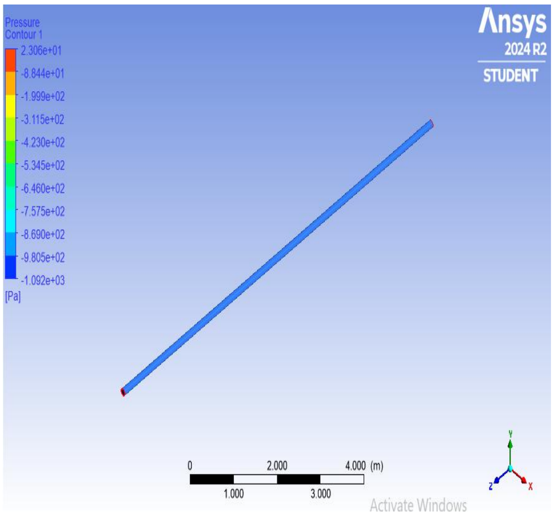

Fig. 4: Pressure profile for fluid A

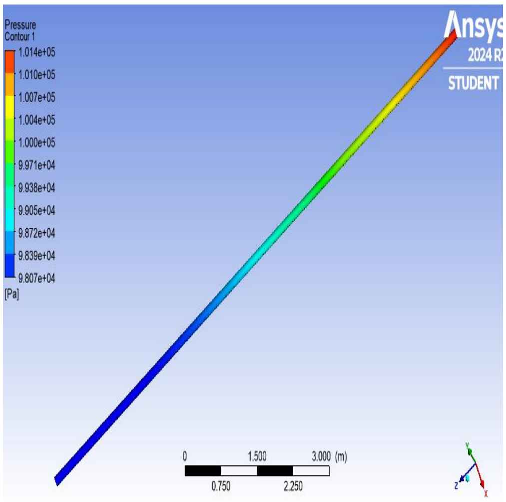

Fig. 5: Pressure profile for fluid B

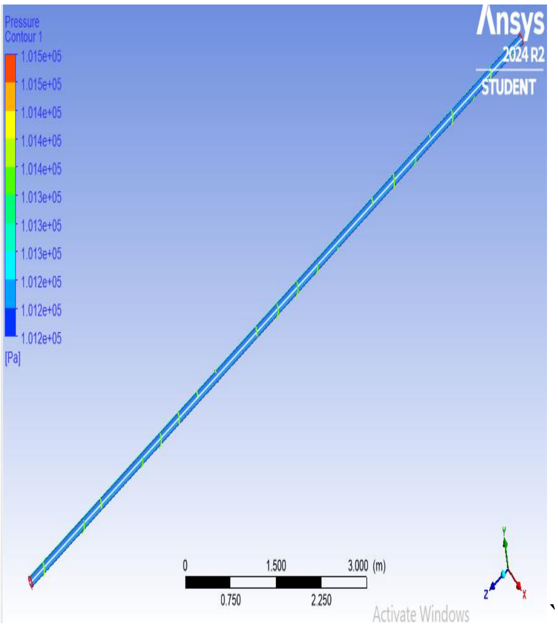

Fig. 6: Pressure profile for fluid C

4.1.6 Velocity Distribution across the corrosive fluids: A, B and C

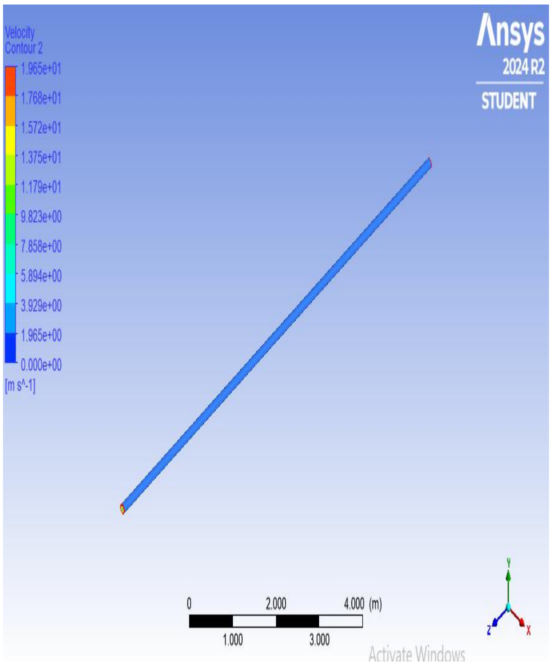

Fig. 7: Pressure profile for fluid A

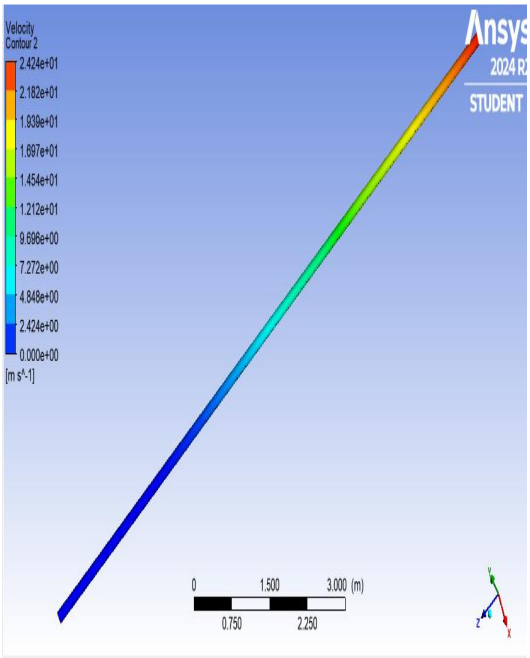

Fig. 8: Pressure profile for fluid B

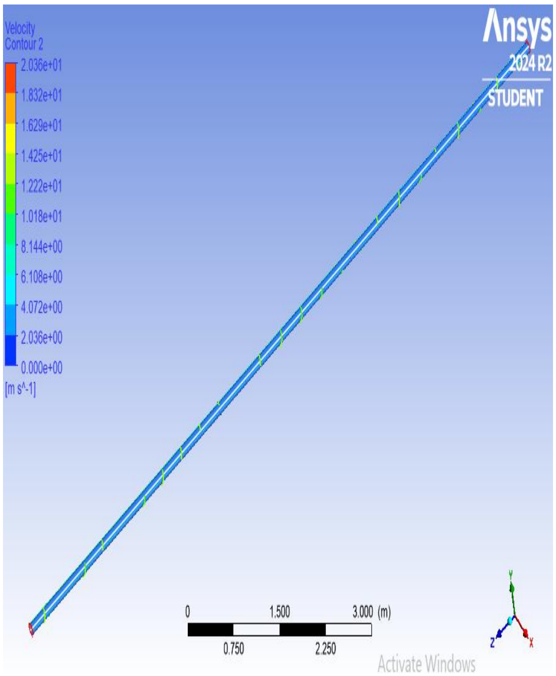

Fig. 9: Pressure profile for fluid C

4.1.7 The pipe performance data for various corrosive fluids at the inlet and exit

Table 8: Pipe performance for different fluids

Corrosive fluid	Inlet pressure (kPa)	Outlet pressure (kPa)	Inlet velocity (m/s)	Outlet velocity (m/s)

H_2O	-109.2	23.06	0.00	19.6
HCl	101.2	101.5	0.00	24.2
H_2O_2	980.7	101.4	0.00	20.3

4.2 Discussions of Result

The wall roughness of the pipe had the greatest influence on the fluid flow performance. To study the influence mechanism of wall roughness on pipe flow, the presented study compared and analysed the internal flow within the pipe for different rough wall conditions using various corrosive fluids under specific boundary conditions. Figures 4 - 6 shows the total pressure contours along the pipe's cross-sectional area for the corrosive fluids: (A) - Hydrogen peroxide (H_2O_2), (B) - Water (H_2O), and (C) - Hydrochloric acid (HCl). Figures 7 - 9 presents the velocity contours of the flow through the pipe for these fluids.

4.2.1 Pressure distribution

Figures 4 - 6 shows the minimum total pressure contours for the fluids (H_2O, H_2O_2, and HCl) flowing through the pipe. The inlet and outlet pressure for water (H_2O) was observed to be −109.2 kPa and 23.06 kPa, respectively. This indicates a moderate pressure drop, suggesting the presence of frictional resistance within the pipe. This behaviour is characteristic of laminar flow, particularly under the given steady-state conditions, though turbulence could occur at higher flow rates due to water's relatively low viscosity. As the fluid traverses the pipe, the pressure decreases steadily, with noticeable drops at regions of greater resistance. However, since the pipe is straight and lacks bends, contractions, or rough surfaces, the pressure drop can primarily be attributed to wall friction along the pipe's length.

For hydrogen peroxide (H_2O_2), a substantial pressure drop is observed, with an inlet pressure of 980.7 kPa and an outlet pressure of 101.4 kPa. This significant pressure decrease arises from the increased flow resistance due to the higher density and viscosity of H_2O_2 compared to water. The flow in this case is likely laminar, or at least in the transitional regime, as viscous forces dominate over inertial forces. The pressure distribution along the pipe decreases sharply, with the greatest losses occurring in areas with higher resistance. In this case, however, the straight pipe geometry minimizes abrupt changes, so the observed pressure drop is primarily due to fluid properties. In the case of hydrochloric acid (HCl), the inlet and outlet pressures are 101.2kPa and 101.5kPa, respectively. This indicates a negligible pressure drop across the pipe, suggesting that the flow faces minimal resistance. This behaviour could imply either laminar flow with a very low velocity or a situation where the flow faces minimal frictional losses due to the physical characteristics of the fluid, such as its lower viscosity compared to H_2O_2.

4.2.2 Velocity distribution

Figure 7 - 9 shows the minimum and maximum velocity contours of the fluids (H_2O, H_2O_2, and HCl) moving through the pipe. The minimum velocity for all fluids is 0.00 m/s, while the maximum velocity values are 19.6m/s for water, 24.2m/s for hydrogen peroxide (H_2O_2), and 20.3m/s for hydrochloric acid (HCl).

For water (H_2O), the velocity increases significantly along the pipe's length, with an inlet velocity of 0.000m/s and an outlet velocity of 19.6m/s. The velocity profile indicates a steady acceleration of the fluid due to the pressure gradient driving the flow. The initial 0.000m/s velocity suggests stagnant or very low flow at the entrance, which transitions to a steady flow along the pipe. This acceleration is likely caused by the gradual conversion of pressure energy into kinetic energy. The velocity distribution for water shows a significant rise toward the outlet, reflecting a smooth laminar flow characteristic, as the fluid accelerates uniformly without turbulence.

For hydrogen peroxide (H_2O_2), the velocity also increases from 0.000m/s at the inlet to 24.2m/s at the outlet, showing a moderate velocity rise. The higher viscosity and density of H2O2 result in greater resistance to flow, limiting its acceleration compared to water. The 0.000m/s inlet velocity indicates a slow initiation of flow, and the gradual increase along the pipe reflects the steady overcoming of viscous resistance. The velocity profile for H_2O_2 likely shows a parabolic distribution, with the highest velocities at the pipe centre and slower velocities near the wall due to viscous drag. For hydrochloric acid (HCl), the velocity increases from 0.000m/s at the inlet to 20.3m/s at the outlet, representing a small but noticeable acceleration. HCl relatively low viscosity compared to H_2O_2 means it encounters less resistance, but the velocity increase is still less significant than water. The initial stagnant flow at the inlet transitions to a steady flow downstream. The velocity distribution for HCl is also expected to be parabolic, with the highest velocities at the pipe's centre and lower velocities near the wall due to frictional effects.

4.3 Validation of Results

The simulation results for the laminar flow of water (H_2O), hydrogen peroxide (H_2O_2), and hydrochloric acid (HCl) in a steel pipe under steady-state conditions provide significant insights into their flow dynamics. For water, the inlet pressure of -109.2 kPa and outlet pressure of 23.06 kPa indicate a considerable pressure drop due to frictional resistance, while the velocity increases from 0.000 m/s to 19.6 m/s as the flow accelerates along the pipe. This behavior aligns with the study by (Xu et al., 2021), which reported similar trends for low-viscosity fluids in industrial pipelines under laminar flow regimes.

Hydrogen peroxide, with an inlet pressure of 980.7 kPa and an outlet pressure of 101.4 kPa, shows a significant pressure drop due to its higher density and viscosity, resulting in a moderate velocity increase from 0.000 m/s to 20.3 m/s. These results are consistent with Singh et al. (2020), who observed steep pressure drops and slower acceleration in viscous fluid flow.

In contrast, hydrochloric acid exhibits minimal pressure variation, with the inlet and outlet pressures being 101.2 kPa and 101.5 kPa, respectively. Its velocity increases from 0.000 m/s to 24.2 m/s, indicating lower resistance compared to water and hydrogen peroxide due to its lower viscosity. These observations are supported by Ahmed et al. (2019), who reported negligible pressure changes and smooth flow behaviour for low viscosity corrosive fluids in steel pipes. The results validate the simulation accuracy and highlight the distinct flow characteristics of the three fluids, showing strong agreement with established literature.

5.0 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusion

In summary, the computational analysis of the existing drilling fluid line operation has provided valuable insights into both pressure and velocity distribution within the system. The results reveal significant variations in pressure gradients along the fluid line, with certain regions exhibiting high-pressure zones that may contribute to energy losses and potential wear on the pipeline. Additionally, the velocity distribution analysis highlights areas of uneven flow, including zones of high velocity that could lead to turbulence and inefficiencies, as well as low-velocity regions that may cause sedimentation or blockages.

These findings emphasize the importance of optimizing the fluid line design and operational parameters to improve the overall efficiency and reliability of the system. By addressing pressure and velocity irregularities, the drilling fluid line can achieve enhanced performance, reduced energy consumption, and extended operational life.

5.2 Recommendation

For future research, the following recommendations are put forward:

1. *Geometry Optimization*: Future studies should explore the redesign of pipeline geometry to minimize pressure fluctuations and ensure a uniform velocity profile. This could include testing alternative shapes or smoothing transitions at critical regions.
2. *Multi-phase Flow Analysis*: Investigate the behaviour of drilling fluid under multi-phase flow conditions, which often occur in real-world operations, to improve the accuracy of computational models and operational strategies.

3. *Turbulence Mitigation*: Research into techniques to reduce turbulence, such as the application of flow conditioners or advanced coatings, could further improve the efficiency and stability of the drilling fluid line.
4. *Thermal Effects:* Incorporate thermal analysis in future simulations to study the impact of temperature variations on both pressure and velocity distributions, as these can significantly influence fluid properties.
5. *Advanced Monitoring Systems*: Develop and implement advanced monitoring technologies, such as real-time sensors, to validate simulation findings and detect operational inefficiencies promptly.
6. *Alternative Fluids:* Explore the use of alternative drilling fluids with improved rheological properties to reduce flow resistance and enhance overall system performance.
7. *Experimental Validation*: Conduct experimental studies alongside simulations to validate computational results and ensure the reliability of the proposed improvements in practical scenarios.

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