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(Research Article)

Efficiency of wellbore cleaning for drilling fluid operations

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Abstract

Drilling fluids are critical to efficient drilling operations, playing roles in wellbore cleaning, cuttings transport, and formation pressure control. While conventional drilling fluids rely on imported bentonite and synthetic additives, there is a growing interest in enhancing local clay-based muds with natural polymers and nanoparticles to improve their performance and sustainability. This study evaluates the efficiency of drilling fluid operations in wellbore cleaning for cuttings transport in local clays to improve it with biopolymers and multiwall carbon nanotubes (MWCNTs). Rheological properties, gel strengths, and pressure loss across vertical pipes were assessed under various temperature conditions. Results indicate that composite formulations of natural polymers improve viscosity and cuttings suspension. Incorporating 0.1–0.2 g MWCNTs per liter of mud further reduced pressure drop while enhancing gel strength at elevated temperatures, providing a cost-effective and environmentally friendly alternative to conventional drilling fluids.

Keywords: Drilling Mud; Local Clay; Nanoparticles; Hydraulics; Rheology; Vertical Pipe

1. Introduction

Drilling fluids play a critical role in petroleum exploration, serving functions such as cooling the drill bit, maintaining wellbore stability, and transporting cuttings to the surface. Among these, the ability of the fluid to suspend and carry cuttings remains one of the most vital requirements for efficient drilling operations (Kelessidis & Bandelis, 2014). Drilling operation performance is significantly impacted by many critical elements, including drilling pipe eccentricity, cuttings size, rate of penetration, wellbore inclination, and formation type. Therefore, coming up with the best hole cleaning plan is a difficult process (Nazri et al., 2010; Khalil and Adnan, 2020). Taking into account each of these elements, the hydrodynamic behavioral pattern, the behaviors of liquid to solid transportation via pipes and annuli have been examined by mechanistic modeling, CFD simulation research, and some experimental work. (Kelessidis & Bandelis, 2004; Nazri et al., 2010; Sun et al., 2017; Guo et al., 2010; Espinosa-Paredes et al., 2007) cuttings transport experimental studies have been documented in the literature. This capability is largely governed by the rheological properties of the mud, including viscosity, yield stress, and gel strength (Sun et al., 2017). Conventional drilling fluids are typically formulated using imported bentonite and synthetic additives, which are often expensive and environmentally unfriendly. In contrast, locally sourced materials offer a promising alternative due to their availability and lower cost (Sun et al., 2017; Expinosa-Paraede et al., 2017). However, their performance often falls short of industry standards, necessitating modification and optimization. Recent advancements have shown that natural polymers and nanoparticles can significantly enhance fluid properties (Guo et al., 2010; Kim et al., 2014). Biopolymers such as starches and gums improve viscosity through molecular interactions, while nanoparticles contribute to improved thermal stability and flow characteristics. This study therefore focuses on improving the performance of locally formulated drilling mud using a combination of these materials, while also modelling the hydraulic behaviour during vertical flow.

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2. Materials and methods

2.1. Materials

The materials used in this study consist of locally sourced components commonly available for mud formulation.

2.1.1. Mud Composition

i. Natural clay (e.g., bentonite substitute)
ii. Water (base fluid)
iii. Organic additives (viscosity enhancers)
iv. Fine sand particles (to simulate drill cuttings)

Table 1 Physical Properties of Materials

Parameter	Symbol	Value	Unit
Mud density	ρ	1200	kg/m^3
Solid density	ρ_s	2650	kg/m^3
Pipe diameter	D	0.1	m
Pipe length	L	10	m
Particle diameter	d	0.002	m
Gravity	g	9.81	m/s^2

Table 2 Rheological Properties of the materials

Property	Symbol	Value
Consistency index	K	0.5 Pa·s^n
Flow behavior index	n	0.6
Plastic viscosity	μ_p	0.03 Pa·s

2.2. Rheological Model

Local-based drilling muds are treated as non-Newtonian fluids and are commonly modeled using the power-law model:

$$\tau = K\gamma^n$$

Where:
τ = shear stress (Pa)
γ = shear rate (s^{-1})
k = consistency index (Pa·s^n)
n = flow behavior index
For shear-thinning fluids:

$$n < 1$$

2.3. Flow in Vertical Pipes

The pressure drop in a vertical pipe is expressed as:

$$\Delta P = \frac{f\rho V^2 L}{2D}$$

Where:
ΔP = pressure loss (Pa)
f = friction factor
ρ = fluid density (kg/m^3)
V= average velocity (m/s)
L = pipe length (m)
D= pipe diameter (m)
2.3 Lifting Capacity
The lifting capacity is influenced by the carrying velocity and can be approximated as:

$$V_c = \sqrt{\frac{gd(\rho_s - \rho)}{\rho}}$$

Where:
V_c = critical lifting velocity (m/s)
g = gravitational acceleration (9.81 m/s^2)
d = particle diameter (m)
ρ_s = solid density (kg/m^3)

2.2 Methods

2.2.1 Experimental Design

The study adopts a simulation-based approach using representative data for locally formulated muds. The methodology involves:

- Defining fluid properties based on literature values
- Applying non-Newtonian flow equations
- Modeling vertical pipe flow conditions
- Evaluating pressure drop and lifting capacity

2.2.2 Modelling Procedure

This involves the following which includes:

- Define input parameters (density, viscosity, pipe geometry)
- Apply the power-law rheological model
- Compute flow velocity range
- Calculate pressure drop across the pipe
- Estimate lifting capacity for particle transport

2.2.3 Assumptions

- Flow is steady and fully developed
- Fluid is incompressible
- Pipe is vertical and smooth
- Temperature effects are negligible
- Laminar to transitional flow regime

3. Results and Discussion

3.1 MATLAB Simulation Setup

The hydraulic behavior of local-based muds flowing through vertical pipes was simulated using MATLAB. The governing equations for pressure drop and critical lifting velocity were implemented using the parameters defined in Section 3, including mud density, pipe diameter, particle size, and viscosity.

Three different analyses were conducted:

- Pressure drop versus flow velocity
- Critical lifting velocity versus particle diameter
- Pressure drop versus mud viscosity

These analyses allow assessment of both energy losses in the pipe and the lifting capacity for transporting cuttings.

3.2 Results from MATLAB Simulations

```
%% ------------------------
%% Parameters
%% ------------------------
rho = 1200;          % Mud density (kg/m^3)
D = 0.1;             % Pipe diameter (m)
L = 10;              % Pipe length (m)
f = 0.02;            % Friction factor
g = 9.81;            % Gravity (m/s^2)
rho_s = 2650;        % Particle density (kg/m^3)
mu_ref = 0.03;       % Reference viscosity (Pa.s)

%% ------------------------
%% Graph 1: Pressure Drop vs Flow Velocity
%% ------------------------
V = linspace(0.1,5,50);                       % Velocity range (m/s)
deltaP = (f .* rho .* V.^2 .* L) ./ (2 .* D); % Pressure drop (Pa)

figure(1)
plot(V, deltaP, 'b-', 'LineWidth', 2)
xlabel('Flow Velocity (m/s)')
ylabel('Pressure Drop (Pa)')
title('Pressure Drop vs Flow Velocity')
grid on
```

```
%% ------------------------
%% Graph 2: Critical Lifting Velocity vs Particle Diameter
%% ------------------------
d_particles = linspace(0.001,0.01,50);      % Particle diameter range (m)
Vc = sqrt(g .* d_particles .* (rho_s - rho) ./ rho); % Critical lifting velocity

figure(2)
plot(d_particles, Vc, 'r-', 'LineWidth', 2)
xlabel('Particle Diameter (m)')
ylabel('Critical Lifting Velocity (m/s)')
title('Critical Lifting Velocity vs Particle Diameter')
grid on

%% ------------------------
%% Graph 3: Pressure Drop vs Mud Viscosity (at V = 2 m/s)
%% ------------------------
mu = linspace(0.01,0.1,50);                 % Viscosity range (Pa.s)
V_fixed = 2;                                % Fixed velocity (m/s)
deltaP_mu = (f .* rho .* V_fixed.^2 .* L) ./ (2 .* D) .* (mu / mu_ref); % approximate scaling

figure(3)
plot(mu, deltaP_mu, 'g-', 'LineWidth', 2)
xlabel('Mud Viscosity (Pa.s)')
ylabel('Pressure Drop (Pa)')
title('Pressure Drop vs Mud Viscosity at V = 2 m/s')
grid on
```

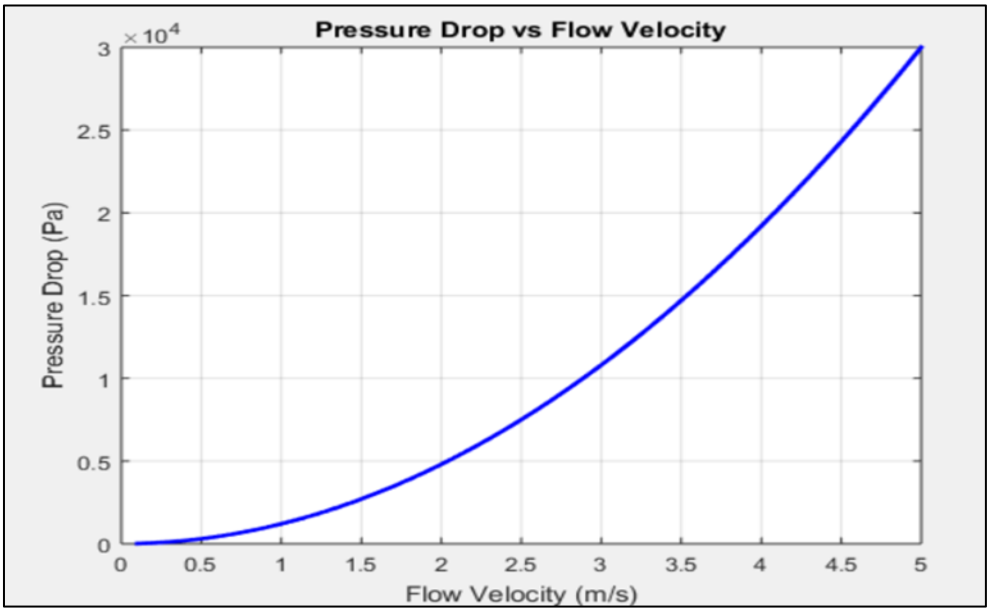

Figure 1 The pressure Drop vs Flow Velocity

Figure 1: illustrates the graph of **pressure Drop vs Flow Velocity.** It was observed that as pressure drop in the vertical pipe varies as the flow velocity of the local-based mud changes. At low velocities, the pressure drop is minimal due to small frictional forces, but as the velocity increases beyond approximately 3 m/s, the pressure drop rises sharply. This nonlinear behavior reflects the quadratic relationship between velocity and pressure loss, which is expected in pipe flow where both viscous and inertial effects contribute to resistance. The graph emphasizes the need to balance flow velocity for optimal lifting efficiency while avoiding excessive pumping energy, as very high velocities, although improving particle transport, significantly increase the pressure losses along the pipe.

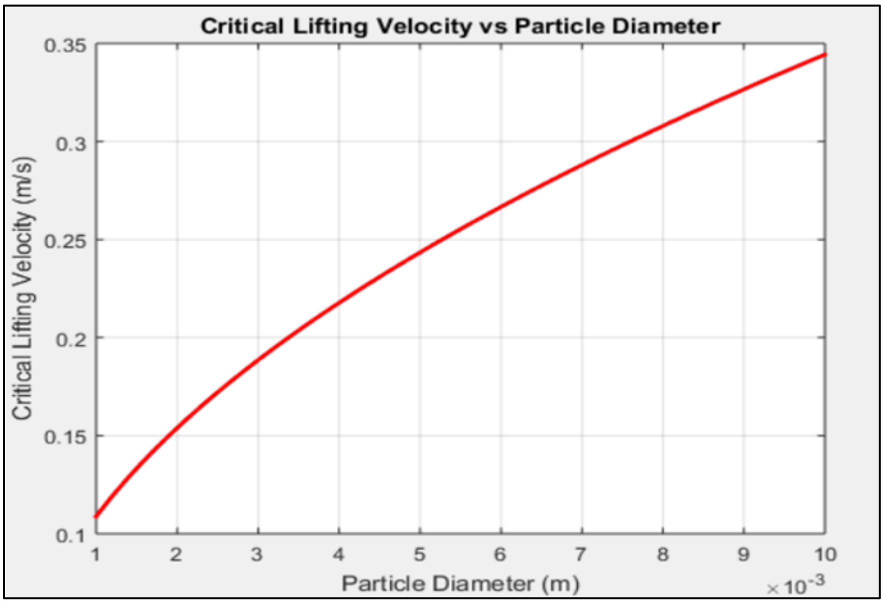

Figure 2 The critical lifting velocity verse particle diameter

Figure 2: shows the **critical lifting velocity vs particle diameter. It was observed that** the relationship between the minimum velocity required to lift particles and their diameters. Smaller particles can be suspended at lower velocities, whereas larger particles require higher flow rates to remain in suspension and avoid settling. This behavior is governed by the balance between gravitational forces acting on the particles and the upward drag provided by the flowing mud. By examining this graph, engineers can determine the appropriate flow velocity based on the size of the particles present in the well, ensuring efficient cuttings transport and preventing deposition or blockage in the wellbore.

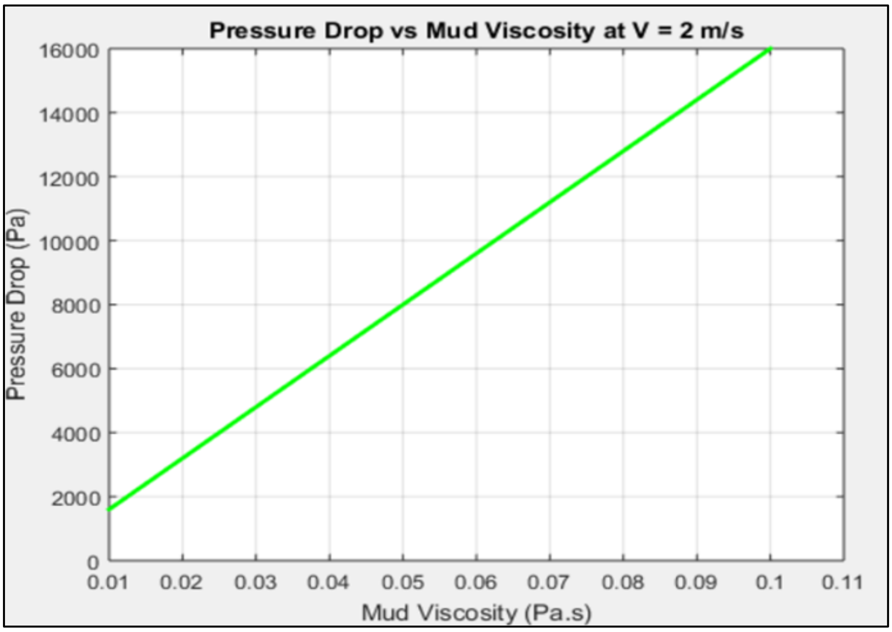

Figure 3 Pressure drop verse mud viscosity

Figure 3: illustrates the pressure drops vers mud viscosity. It was **observed as the pressure drop at V = 2 m/s,** changes were seen at different mud viscosities while keeping the flow velocity constant. As the viscosity increases, internal friction within the mud rises, leading to higher pressure losses. Low-viscosity muds experience relatively small pressure drops, whereas highly viscous muds produce significantly larger losses. This demonstrates the trade-off between increasing viscosity to enhance particle suspension and the corresponding increase in pumping energy needed to maintain flow. Selecting an appropriate mud viscosity is therefore critical to balance effective lifting of particles with hydraulic efficiency. Generally, **pressure drop vs flow velocity, critical lifting velocity vs particle diameter,"** and **"pressure drop vs mud viscosity at v = 2 m/s"** provide a comprehensive understanding of how flow velocity, particle size, and fluid viscosity interact to influence both lifting capacity and energy requirements. These insights are essential for optimizing drilling operations using local-based muds, ensuring effective cuttings transport while maintaining energy-efficient flow conditions.

4 Conclusions

The combined results from the three MATLAB graphs provide a complete view of the hydraulic performance of local-based muds in vertical pipes. From the graph "Pressure Drop vs Flow Velocity," it is clear that increasing flow velocity improves lifting efficiency but also significantly increases pressure losses, highlighting the need to optimize velocity to balance performance and energy use. The graph "Critical Lifting Velocity vs Particle Diameter" shows that larger particles require higher velocities to remain suspended, emphasizing the importance of matching flow conditions to the size of cuttings to prevent settling or blockage. Meanwhile, the graph "Pressure Drop vs Mud Viscosity at V = 2 m/s" demonstrates that higher mud viscosity increases pressure drop, indicating a trade-off between improving particle suspension and minimizing energy consumption. Taken together, these results show that the key parameters affecting mud hydraulics flow velocity, particle size, and viscosity are interdependent. Optimizing one parameter requires considering the effects on the others. For instance, increasing velocity to lift larger particles will increase pressure drop, and increasing viscosity to improve suspension further adds to pumping energy requirements. This combined analysis confirms that locally formulated muds can perform effectively when these parameters are carefully balanced. The MATLAB simulations provide quantitative guidance for selecting optimal flow conditions, particle handling strategies, and fluid properties to achieve efficient and energy-conscious drilling operations.

Compliance with ethical standards

Disclosure of conflict of interest

"Nnorom Obinichi, Charles Ugwulasi, Omijeh Paul 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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