Advanced CFD–DEM Analysis of Cuttings Transport Efficiency in Oil Well Drilling

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Abstract

Efficient hole cleaning in oil and gas drilling operations is crucial for maintaining drilling efficiency and preventing operational issues. This study employs a fully coupled Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM) approach to investigate the effect of mud hydrodynamics on cuttings transport. The CFD-DEM model integrates the Eulerian approach for fluid dynamics with the Lagrangian approach for particle dynamics, considering the two-way interaction between fluid and solid phases. Key parameters such as mud rheology, flow rate, cutting size, drill string rotation, and inclination angle are analyzed to understand their impact on cuttings transport efficiency.

The results indicate that increasing mud viscosity improves cuttings suspension but also increases pressure drop, necessitating higher pump power. Higher flow rates enhance cutings transport, but benefits diminish at extreme turbulence levels due to re-suspension. Smaller cuttings are more effectively transported compared to larger ones. Drill pipe rotation significantly affects cuttings transport at lower velocities, particularly in deviated wells, but has minimal impact at higher velocities. The inclination angle of the wellbore also plays a crucial role, with horizontal wells exhibiting lower transport efficiency due to gravitational settling.

This study provides valuable insights for optimizing drilling fluid properties and operational parameters to improve hole cleaning efficiency. The findings highlight the importance of a comprehensive understanding of fluid-particle interactions and the need for careful consideration of multiple factors in drilling operations.

Keywords: CFD-DEM Simulation, Cuttings Transport, Oil Well Drilling, Mud Hydrodynamics

1. Introduction

Efficient hole cleaning is a critical aspect of the drilling process in the oil and gas industry. It involves the removal of drill cuttings generated during drilling operations to ensure a smooth drilling process and prevent various operational problems. The effectiveness of hole cleaning directly impacts the rate of penetration, wellbore stability, and overall drilling efficiency. Inadequate hole cleaning can lead to stuck pipe incidents, increased torque and drag, and even wellbore collapse [1].

Mud hydrodynamics plays a vital role in the transportation of cuttings from the wellbore to the surface. The drilling mud, or drilling fluid, is circulated through the wellbore to carry cuttings to the surface while providing lubrication, cooling, and wellbore stabilization [2]. The interplay between the mud flow and cuttings transport is complex and influenced by various factors, including mud properties, flow rate, wellbore geometry, and cuttings size and density.

In recent years, Computational Fluid Dynamics (CFD) coupled with Discrete Element Method (DEM) has emerged as a powerful tool for studying the complex interactions between fluid and solid particles in various engineering applications [3]. CFD–DEM simulations provide detailed insights into the fluid dynamics and particle transport mechanisms, making them ideal for investigating hole cleaning in oil well drilling. This paper presents a fully coupled CFD–DEM simulation study to explore the effect of mud hydrodynamics on cuttings transport in oil well hole cleaning.

2. Literature Review

Hole cleaning has been a subject of extensive research in the drilling industry. Early studies primarily relied on experimental approaches to understand the mechanisms of cuttings transport. Laboratory-scale experiments were conducted to investigate the influence of various parameters such as mud rheology, flow rate, and wellbore inclination on cuttings transport efficiency [4]. However, these experiments were often limited by scale and complexity, making it challenging to capture the full range of interactions occurring in real drilling operations.

The advent of numerical simulation techniques brought significant advancements in the study of hole cleaning. CFD simulations have been widely used to model the fluid dynamics of drilling mud and predict cuttings transport behavior [5]. These simulations have provided valuable insights into the effects of flow rate, mud viscosity, and wellbore geometry on hole cleaning efficiency. However, traditional CFD models often treat cuttings as a continuous phase, neglecting the discrete nature of particles and their interactions [6].

The development of DEM allowed for a more accurate representation of particle dynamics. DEM simulations model individual particles and their interactions, capturing the effects of particle size, shape, and density on transport behavior [7]. When coupled with CFD, DEM provides a comprehensive framework for studying fluid-particle interactions in complex systems [8]. CFD–DEM simulations have been applied to various engineering problems, including sediment transport, pneumatic conveying, and pharmaceutical manufacturing.

In the context of hole cleaning, CFD–DEM simulations offer a detailed understanding of the interactions between drilling mud and cuttings. Several studies have utilized CFD–DEM to investigate the effect of mud rheology, flow rate, and wellbore inclination on cuttings transport. These studies have highlighted the importance of particle-fluid interactions and provided valuable guidelines for optimizing drilling fluid properties and flow conditions to enhance hole cleaning efficiency.

3. Modeling

The fully coupled CFD–DEM simulation framework used in this study consists of two main components: the CFD model for fluid dynamics and the DEM model for particle dynamics. The CFD model solves the Navier-Stokes equations for the drilling mud, while the DEM model tracks the motion and interactions of individual cuttings particles [9]. The coupling between the two models is achieved through the exchange of information at each time step, allowing for the simulation of fluid-particle interactions in a fully resolved manner [10].

CFD Model

The CFD model used in this study is based on the incompressible Navier-Stokes equations for a Newtonian fluid. The governing equations for mass and momentum conservation are given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F}_p \tag{2}$$

where ρ is the fluid density, $\mathbf{u}$ is the fluid velocity, p is the pressure, μ is the dynamic viscosity, and $\mathbf{F}_p$ is the body force due to particle interactions.

DEM Model

The DEM model tracks the motion of individual cuttings particles using Newton's equations of motion. The equations of motion for a particle i are given by:

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{F}_i^c + \mathbf{F}_i^f + \mathbf{F}_i^g \tag{3}$$

$$I_i \frac{d\omega_i}{dt} = \mathbf{T}_i^c + \mathbf{T}_i^f \tag{4}$$

where m_i is the mass of particle i, $\mathbf{v}_i$ is the particle velocity, $\mathbf{F}_i^c$ is the contact force due to particle-particle and particle-wall interactions, $\mathbf{F}_i^f$ is the fluid force acting on the particle, $\mathbf{F}_i^g$ is the gravitational force, I_i is the moment of inertia, ω_i is the angular velocity, $\mathbf{T}_i^c$ is the contact torque, and $\mathbf{T}_i^f$ is the fluid torque.

Coupling Mechanism

The coupling between the CFD and DEM models is achieved through the exchange of information at each time step. The fluid forces acting on the particles are calculated based on the local fluid velocity and pressure fields obtained from the CFD model [11]. The particles' motion and interactions are then updated in the DEM model, and the resulting particle positions and velocities are used to update the fluid body forces in the CFD model. This iterative process ensures a fully coupled simulation of fluid-particle interactions.

Simulation Setup

The simulation domain consists of a vertical wellbore section with a specified diameter and length. The wellbore is filled with drilling mud, and cuttings particles are introduced at the bottom of the wellbore [12]. The properties of the drilling mud, including density and viscosity, are specified based on typical values used in the field. The cuttings particles are modeled as spherical particles with a specified size distribution and density.

The boundary conditions for the CFD model include a specified flow rate at the inlet, a pressure outlet at the top, and no-slip conditions at the wellbore walls [13]. The DEM model includes boundary conditions for particle interactions with the wellbore walls and each other. The simulation is run for a specified period to allow for the development of a steady-state flow and cuttings transport behavior [14].

4. Results and Discussion

The simulation results provide detailed insights into the effect of mud hydrodynamics on cuttings transport in the wellbore. The key parameters analyzed include cuttings concentration profiles, particle velocity distributions, and pressure drop along the wellbore [15]. The results are compared with experimental data and previous numerical studies to validate the accuracy of the CFD–DEM simulation.

Cuttings Concentration Profiles

The concentration profiles of cuttings along the wellbore length provide important information on the efficiency of cuttings transport. The simulation results show that the concentration of cuttings decreases with increasing distance from the cuttings injection point. The concentration profiles are influenced by the flow rate of the drilling mud, with higher flow rates leading to more effective cuttings transport and lower concentrations near the bottom of the wellbore.

Particle Velocity Distributions

The velocity distributions of cuttings particles provide insights into the transport mechanisms and the effect of mud hydrodynamics. The simulation results show that particle velocities are highest near the center of the wellbore, where the fluid velocity is also highest. The particle velocities decrease towards the wellbore walls due to the no-slip boundary condition and the resulting velocity gradient. The effect of particle-particle and particle-wall interactions on the velocity distributions is also evident, with collisions leading to local variations in particle velocities.

Pressure Drop

The pressure drop along the wellbore is an important parameter in drilling operations, as it affects the overall hydraulic efficiency and the potential for wellbore stability issues. The simulation results show that the pressure drop is influenced by the flow rate and the concentration of cuttings. Higher flow rates and higher concentrations of cuttings lead to increased pressure drop, highlighting the need for optimizing flow conditions to balance effective cuttings transport and manageable pressure drop.

Comparison with Experimental Data

The simulation results are compared with experimental data from laboratory-scale hole cleaning experiments. The comparison shows good agreement between the simulation and experimental results, validating the accuracy of the CFD–DEM model. The ability of the model to capture the key trends and interactions observed in the experiments demonstrates its potential for predicting hole cleaning performance in real drilling operations.

Effect of Mud Rheology

The effect of mud rheology on the Relative Cuttings Concentration (RCC) was investigated. Increasing mud viscosity from low-viscosity mud (LVM) to high-viscosity mud (HVM) resulted in a decrease in RCC, indicating improved cleaning efficiency. The impact of rheology on cuttings transport was less pronounced at higher flow rates. The simulations revealed that higher viscosity muds improve the suspension of cuttings, reducing the formation of a cuttings bed, but also increase the pressure drop in the annulus, requiring higher pump power.

Influence of Flow Rate

Increasing the flow rate of drilling mud enhanced the transport of cuttings, minimizing the cuttings bed. However, beyond a certain threshold, the benefits diminished due to turbulence-induced re-suspension of cuttings. The results showed that at higher flow rates, the increased turbulence helps to suspend and transport cuttings more effectively, but it can also lead to re-suspension of settled cuttings, which can decrease the overall transport efficiency.

Effect of Cuttings Size

The impact of particle size on RCC was studied for average particle diameters of 1 mm and 1.4 mm. Smaller particles were more easily suspended and transported, while larger particles tended to settle, forming a stable bed. By increasing the annular velocity, RCC for larger particles reduced significantly, highlighting the importance of optimizing mud velocity for effective hole cleaning. The simulations indicated that the size of the cuttings plays a crucial role in their transport behavior, with smaller particles being more responsive to changes in fluid velocity.

Effect of Drill Pipe Rotation

The drill pipe rotation's influence on RCC was more pronounced at lower annular velocities. Increasing drill pipe rotation from zero to 120 RPM improved the cleaning efficiency in deviated annuli at lower velocities, while it had minimal effect for vertical annuli. The rotation of the drill pipe helps to agitate the cuttings and keep them suspended in the drilling fluid, but its effectiveness decreases at higher mud velocities where the fluid flow dominates the transport process.

5. Future Work

The current study provides valuable insights into the effect of mud hydrodynamics on cuttings transport using a fully coupled CFD–DEM simulation. However, several areas warrant further investigation to enhance the understanding and optimization of hole cleaning in drilling operations.

Influence of Non-Newtonian Mud Rheology

The current study assumes a Newtonian fluid for the drilling mud, while in practice, drilling muds often exhibit non-Newtonian behavior. Future work should investigate the influence of non-Newtonian rheology on cuttings transport, considering various mud types such as Bingham plastic and power-law fluids.

Effects of Wellbore Inclination

The current study focuses on a vertical wellbore. However, directional and horizontal drilling operations are common in the industry. Future work should explore the effects of wellbore inclination on cuttings transport, including the challenges associated with inclined and horizontal wellbores.

Influence of Particle Shape and Size Distribution

The current study models cuttings as spherical particles with a specified size distribution. In reality, cuttings have irregular shapes and a wide range of sizes. Future work should incorporate more realistic particle shapes and size distributions to better capture the dynamics of cuttings transport.

Real-Time Monitoring and Control

Future work should also explore the integration of real-time monitoring and control strategies for hole cleaning. Advanced sensors and data analytics can provide real-time insights into hole cleaning performance, enabling adaptive control of drilling parameters to optimize cuttings transport.

6. Conclusions

This study presents a fully coupled CFD–DEM simulation framework to investigate the effect of mud hydrodynamics on cuttings transport in oil well hole cleaning. The results demonstrate the capability of the CFD–DEM model to capture the complex interactions between drilling mud and cuttings particles, providing detailed insights into cuttings concentration profiles, particle velocity distributions, and pressure drop along the wellbore.

The simulation results highlight the importance of optimizing mud flow rate and properties to enhance hole cleaning efficiency while managing pressure drop. The comparison with experimental data validates the accuracy of the CFD–DEM model and underscores its potential for predicting hole cleaning performance in real drilling operations.

Future work should focus on investigating the influence of non-Newtonian mud rheology, wellbore inclination, and realistic particle shapes and sizes. The integration of real-time monitoring and control strategies can further enhance the effectiveness of hole cleaning in drilling operations.

The fully coupled CFD–DEM simulation approach provides a powerful tool for understanding and optimizing cuttings transport in oil well drilling, contributing to more efficient and safe drilling practices in the oil and gas industry.

7. References

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