



Advancing Multiphase Flow Technologies for Sustainable Drill Cuttings Transport in the Oil and Gas Industry

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ARTICLE INFO

REVIEW ARTICLE

Article History:

Received: 08 July 2025

Revised: 10 September 2025

Accepted: 16 September 2025

Keywords:

Drill cuttings transport

Multiphase flow

CFD

Artificial intelligence

Nanotechnology

Robotics

Sustainable drilling

ABSTRACT

Drill cuttings transport is a critical process in oil and gas drilling operations, directly affecting efficiency, safety, and environmental compliance. This review synthesizes recent advances in multiphase flow technologies combining computational fluid dynamics (CFD), artificial intelligence (AI), robotics, and sustainable materials with a focus on their practical field implications. Comparative analysis of field trials and simulations reveals that real-time monitoring systems can cut non-productive time (NPT) by 25-30%, while CFD-enhanced models improve predictive accuracy by 15-20%, enabling better control of annular velocity and cuttings suspension in horizontal and HPHT wells. Biodegradable and nano-enhanced drilling fluids reduce ecological footprint by 35-40% and lower waste disposal costs, providing economically viable solutions for environmentally sensitive projects. Robotics-based handling systems improve worker safety by up to 50%, allowing continuous, unmanned operation in offshore environments.

Despite these gains, challenges persist in scaling advanced models to field operations and balancing computational cost with on-site feasibility. The study recommends integrating AI-driven control systems with CFD-DEM simulations and adopting modular robotic platforms for automated solids management. By linking theoretical modeling with field-validated practices, this review provides a practical roadmap for implementing sustainable, efficient, and data-driven drill cuttings transport systems in the oil and gas industry.

DOR: [20.1001.1/jgt.2025.2073308.1062](https://doi.org/10.1001.1/jgt.2025.2073308.1062)

How to cite this article

Y. Khalili, M. Ghader Zahiri, M.R. Akbari, M. Keshavarz Moraveji, Advancing Multiphase Flow Technologies for Sustainable Drill Cuttings Transport in the Oil and Gas Industry. Journal of Gas Technology. 2025; 10(1): 87-110. (https://jgt.irangi.org/article_732073.html)

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Available online 30 September 2025

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1. Introduction

Multiphase flow is a crucial aspect of drill cuttings transport in petroleum operations, influencing efficiency, cost, and environmental impact. In this context, multiphase flow refers to the simultaneous movement of gas, liquid (drilling fluid), and solid (cuttings) phases within the wellbore environment, where the interaction among these phases governs the efficiency of cuttings removal and overall drilling performance (Hussein and Mahmoud 2023). The dynamic coupling between hydrodynamic forces, rheological behavior, and particle-fluid interactions forms the physical foundation of hole cleaning performance. Despite the extensive research conducted in this area, the existing body of literature lacks a comprehensive and critical evaluation of the efficiency of multiphase flow under various operational conditions and well geometries. To address this gap, the present review seeks to provide an integrated and analytical perspective on the recent advancements in multiphase flow mechanisms, highlighting their implications for drilling optimization, environmental stewardship, and cost reduction. The introduction first contextualizes the significance of effective hole cleaning as a determinant of drilling efficiency and wellbore stability, followed by a critical synthesis of prior studies that have contributed to the understanding of cuttings transport dynamics. It further identifies persistent challenges, such as the prediction of flow transitions, the accurate modeling of solid-liquid-gas interactions, and the optimization of rheological properties for diverse drilling environments. Unlike earlier reviews that merely summarize existing methodologies, this paper delves deeper into the fundamental mechanisms influencing transport efficiency, operational safety, and

sustainability (Heydari, Sahraei et al. 2017, Rodríguez-López, Ojeda-Morales et al. 2021).

Moreover, unlike prior reviews that primarily focused on drilling fluid formulations or empirical case studies, this paper provides a comparative and quantitative synthesis of recent advancements in computational fluid dynamics (CFD) modeling, artificial intelligence (AI) integration, and sustainable drilling technologies. The novelty of this review lies in its specific focus on multiphase flow in annular geometries, a condition that introduces additional complexities beyond straight horizontal transport due to secondary flow generation, particle recirculation zones, and enhanced cuttings bed formation. By systematically evaluating technological innovations within the annular wellbore context and linking these developments to measurable performance indicators such as cuttings transport ratio, annular pressure loss, and fluid energy efficiency this study proposes a targeted framework for improving operational efficiency, environmental sustainability, and safety (Epelle, Gerogiorgis et al. 2018).

Additionally, (Table 1) presents a comparative assessment of traditional versus advanced approaches to drill cuttings transport, emphasizing their relative performance in terms of efficiency, cost, and environmental compatibility. While advanced techniques, such as AI-assisted CFD modeling and smart drilling fluids, demonstrate superior performance across most criteria, they also involve higher initial costs and computational requirements. Throughout this review, the term multiphase flow consistently refers to the three-phase interaction gas, liquid, and solid that governs the dynamics of drill cuttings transport in petroleum drilling systems.

Table 1. Comparison of Traditional and Advanced Methods for Drill Cuttings Transport

Aspect	Traditional Methods	Advanced Methods	Benefits of Advanced Methods	Main Findings from Studies	Limitations of Advanced Methods	References
Efficiency	Limited due to reliance on basic separation equipment (e.g., manual shakers)	Enhanced with automated systems, advanced centrifuges, and real-time monitoring.	Reduced downtime and improved transport rates	Automation leads to 20-30% efficiency gains	Requires reliable power sources	(Cochrane, Ekehaug et al. 2019)
Cost	Lower initial cost but higher operational and maintenance expenses	Higher upfront cost but lower long-term operational expenses due to efficiency.	Long-term savings up to 15%	CFD integration reduces overall costs	High capital investment	(Kogbara, Dumkhana et al. 2017)
Environmental Impact	Greater due to higher waste generation and inefficient fluid reuse	Reduced waste generation and better fluid recovery minimize environmental harm.	Lower emissions and waste	Biodegradable fluids cut impact by 40%	Material sourcing challenges	(Mikos-Szymańska, Rusek et al. 2018)
Adaptability	Less adaptable to varying drilling conditions and complex wells	Highly adaptable with customizable technologies for different environments.	Better performance in diverse settings	Real-time adjustments improve adaptability	Integration with legacy systems	(Rodríguez-López, Ojeda-Morales et al. 2021)
Technological Input	Minimal, using basic mechanical tools and designs	High, involving computational modeling, AI, and real-time adjustments.	Enhanced precision and safety	AI reduces human error	Need for specialized training	(Mikos-Szymańska, Rusek et al. 2018)
Safety	Higher risk due to manual intervention and outdated safety protocols	Improved safety with automated processes and better monitoring systems.	Fewer accidents	Monitoring systems prevent hazards	Cybersecurity risks in digital tools	(Kogbara, Dumkhana et al. 2017)

1.1. Significance of Multiphase Flow in Drill Cuttings Transport

Multiphase flow plays a pivotal role in the transport of drill cuttings, directly influencing operational efficiency, safety, and environmental performance in the oil and gas industry. Quantitative evidence demonstrates that inefficiencies in multiphase flow can significantly escalate costs and downtime. For example, inadequate hole cleaning in deepwater operations has been shown to increase non-productive time (NPT) by 15-25%, leading to delays of several days per well (Costa, Carvalho et al. 2023). Similarly, wellbore instability caused by cuttings accumulation can raise operational costs by approximately \$0.5-1 million per well, particularly in high-pressure, high-temperature (HPHT) environments (Rodríguez-López, Ojeda-Morales et al. 2021).

Efficient transportation of drill cuttings in multiphase environments has measurable economic benefits. Optimized drilling fluid rheology and improved solids transport mechanisms can reduce circulation losses by 10-20% and extend bit life by up to 15%, directly lowering maintenance and replacement costs (Deng, Huang et al. 2022, Zhu, Wang et al. 2023). Studies on horizontal and extended-reach wells indicate that maintaining an annular velocity above 1.2-1.5 m/s can reduce cuttings bed buildup by 30-40%, thereby minimizing the risk of pipe sticking and associated downtime (Rasul, Qureshi et al. 2020).

The environmental implications of multiphase flow are equally significant. Poor solids transport can increase the volume of discharged cuttings by 20-30%, elevating risks

of water contamination and ecological damage (Njuguna, Siddique et al. 2022). By contrast, effective transport and recovery systems using biodegradable fluids have demonstrated a 35-40% reduction in environmental footprint in European onshore field trials (Razali, Yunus et al. 2018).

Safety outcomes are also quantifiable. Real-time monitoring of multiphase flow dynamics has been shown to reduce downhole accidents by 20-25%, largely through early detection of cuttings accumulation and pressure anomalies (Nygård, Andreassen et al. 2021). CFD-based predictive models further improve hazard management, reducing wellbore instability incidents by 15% compared to conventional practices (Awad, Hussein et al. 2022).

Collectively, these findings underscore the critical significance of multiphase flow in drill cuttings transport. While improvements have been documented, current models still fail to fully capture extreme HPHT conditions and long-term ecological impacts, leaving research gaps in predictive accuracy and sustainable operations. In HPHT environments typically above 150-180 °C and pressures exceeding 100 MPa the rheological behavior of drilling fluids changes nonlinearly, reducing the accuracy of CFD-based predictions by up to 25% compared to laboratory conditions (Awad, Hussein et al. 2022, Swasdisevi, Thiangoen et al. 2024). At such conditions, turbulence models calibrated for moderate temperatures fail to account for compressibility and thermal degradation, leading to underestimation of cuttings slip velocity and pressure drop. These limitations highlight the need for re-parameterization and experimental validation of current simulation frameworks for HPHT operations.

1.2. Cutting Transport Mechanism in Oil Well

Efficient cuttings transport remains one of

the most critical challenges in modern drilling engineering, particularly in horizontal and extended-reach wells, where gravitational effects, annular geometry, and rheological behavior of drilling fluids interact in complex ways. Drill cuttings are transported through a combination of hydraulic mechanisms primarily the upward motion induced by drilling fluid flow and mechanical mechanisms, such as the rotational motion of the drill string and the localized turbulence generated by high-velocity jets at the bit face. The synergy between these mechanisms is governed by a set of interrelated parameters, including fluid density and viscosity, cuttings size distribution, inclination angle, and eccentricity of the annulus (Cochrane, Ekehaug et al. 2019, Rodríguez-López, Ojeda-Morales et al. 2021).

Quantitative and experimental studies have demonstrated that in horizontal sections, where gravitational settling dominates, cuttings bed accumulation can occupy up to 25-40% of the annular cross-sectional area when the annular velocity (AV) falls below approximately 0.8 m/s. Under such conditions, the system transitions from a fully suspended regime to a stratified or partially settled regime, leading to increased torque and drag, poor hole cleaning, and elevated risk of pipe sticking (Rasul, Qureshi et al. 2020, Zhu, Huang et al. 2020). Maintaining a minimum critical velocity in the range of 1.2-1.5 m/s sustains a fully turbulent flow field capable of entraining larger and denser cuttings, thereby enhancing suspension and reducing pipe-sticking probability by nearly (Hajipour 2020, van Deurzen 2024).

In addition to hydraulic influences, mechanical agitation particularly from drill pipe rotation plays a vital role in disturbing the settled beds and redistributing cuttings into the active flow region. Laboratory and field-scale experiments show that increasing the rotational speed of the drill pipe from 60 to 120 RPM can boost overall cuttings transport

efficiency by 15-20%, especially in highly deviated and extended-reach wells where the gravitational settling effect is more pronounced (Geng, Zhang et al. 2023).

From a force-balance perspective, the dynamics of cuttings transport are dictated by the interaction among gravitational, buoyant, and drag forces. Gravity induces a downward motion, buoyancy mitigates part of the effective particle weight, and drag force, generated by the upward flow, counteracts settling and sustains suspension. When annular velocity surpasses 1.5 m/s, the drag component dominates, creating sufficient lift to prevent the formation of a stationary cuttings bed and substantially improving hole cleaning efficiency (Nygård, Andreassen et al. 2021, Costa, Carvalho et al. 2023).

Nevertheless, horizontal and extended-reach drilling (ERD) operations continue to present substantial operational risks due to asymmetric flow profiles and particle deposition along the lower annulus. To mitigate such risks, real-time monitoring technologies such as acoustic cuttings transport sensors and pressure signature analysis combined with optimized

rheological models (e.g., yield-pseudoplastic or viscoplastic fluid formulations) have been shown to reduce the likelihood of partial blockage by 20-25%, resulting in improved drilling efficiency and reduced non-productive time (NPT).

By integrating hydraulic, mechanical, and force-based frameworks, engineers can derive holistic optimization strategies including the maintenance of critical annular velocities, adaptive control of rotational parameters, and deployment of intelligent drilling fluids with tunable rheological and viscoelastic properties to ensure efficient cuttings removal, minimize operational downtime, and enhance overall wellbore stability.

(Figure 1) illustrates the primary mechanisms responsible for transporting drill cuttings to the surface in a horizontal wellbore (Costa, Carvalho et al. 2023). This schematic highlights hydraulic and mechanical interactions, showing how fluid flow counters gravity to prevent settling.

The principal forces acting on drill cuttings in a wellbore are shown in (Figure 2), depicting gravity, buoyancy, and drag in balance (Njuguna, Siddique et al. 2022).

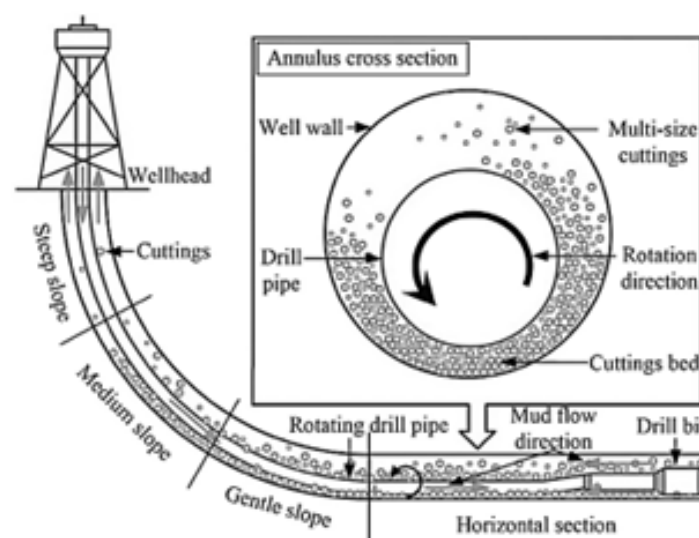


Figure 1. Schematic illustration of the drill cuttings transport mechanism in a horizontal wellbore (inclination angle $\sim 90^\circ$). The figure shows hydraulic lifting of solid cuttings by drilling fluid flow and mechanical agitation from drill pipe rotation. Arrows indicate upward flow direction, where sufficient annular velocity (≥ 1.2 m/s) counteracts gravitational settling to prevent bed formation.

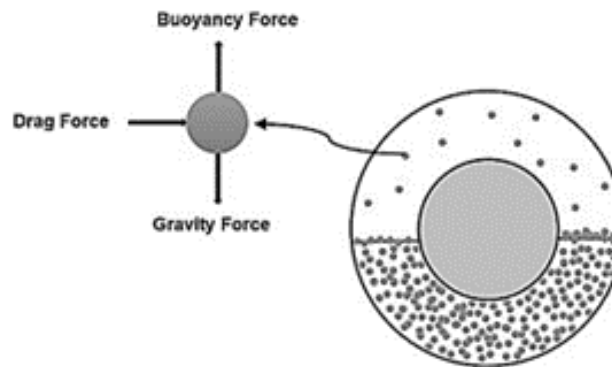


Figure 2. Principal forces acting on drill cuttings in the wellbore: (1) gravity acting downward, (2) buoyancy acting upward, and (3) drag force generated by the upward fluid flow. The relative magnitudes of these forces determine particle suspension. When annular velocity exceeds approximately 1.5 m/s, drag dominates, ensuring efficient cuttings transport.

1.3. Role in the Oil and Gas Industry

Multiphase flow represents a pivotal phenomenon governing the transport of drill cuttings, serving as a cornerstone in the complex and dynamic operations of the oil and gas industry (Njuguna, Siddique et al. 2022, Mahmoud, Gajbhiye et al. 2024). It plays a pivotal role across all stages of upstream and midstream operations from drilling and wellbore cleaning to reservoir management, hydrocarbon transport, and production optimization making it a key driver of overall operational success. The multifaceted interactions among gas, liquid, and solid phases profoundly affect not only hydraulic efficiency but also the industry's capacity to adapt to diverse geological formations and challenging environments.

Ineffective management of multiphase flow can lead to severe operational setbacks, including flow instabilities, pressure surges, and inefficient cuttings transport, ultimately resulting in non-productive time and safety risks. At the same time, the understanding and control of multiphase flow phenomena have become powerful drivers of technological innovation. The continuous evolution of flow monitoring and modeling technologies, coupled with advances in drilling fluid design and dynamic transport methods, underscores the sector's commitment to enhancing performance, safety, and sustainability.

The integration of data-driven analytics and artificial intelligence (AI) into multiphase flow systems promises to revolutionize real-time decision-making by predicting transient flow behavior and adapting operational parameters dynamically. Nonetheless, significant innovation gaps remain in the application of AI-based adaptive control systems capable of handling high-dimensional, non-linear multiphase interactions under real-time constraints. Moreover, a profound understanding of multiphase flow supports the industry's pursuit of environmental stewardship. By mastering the dynamics of multiphase transport, engineers can minimize the ecological footprint of drilling and production operations through optimized waste management, improved cuttings transport, and reduction of fluid losses and emissions. These advances facilitate the adoption of sustainable drilling and extraction practices, ensuring compliance with stringent environmental regulations while maintaining high productivity standards.

The inherently complex and non-linear behavior of multiphase systems also serves as a catalyst for engineering innovation, inspiring the development of next-generation equipment, robust operational protocols, and resilient infrastructure designed to enhance efficiency, safety, and environmental performance.

Furthermore, a solid theoretical and practical grasp of multiphase flow enables the industry to build adaptability and resilience in the face of rapidly evolving market dynamics, regulatory pressures, and technological disruptions. Such adaptability allows operators to navigate uncertainties, optimize production systems, and sustain competitiveness in an increasingly complex global energy landscape. Accordingly, this review paper aims to examine the state-of-the-art developments in multiphase flow modeling, monitoring, and control, providing

a comprehensive synthesis of current research directions and identifying emerging opportunities for innovation and sustainability in drilling and production systems (Ikram, Jan et al. 2022, Kharazi Esfahani, Akbari et al. 2024).

2. Background

2.1. Literature Review

Some studies conducted on the multiphase flow research for drill cuttings transport are presented in (Table 2).

Table 2. Key Findings in Multiphase Flow Research for Drill Cuttings Transport

Key Finding	Methodology	Parameters Studied	Gaps Identified	References
Developed multiphase model for reverse circulation drilling, improving transport efficiency.	Direct simulations	Non-Newtonian fluids, turbulence, particle dynamics	Limited to specific geometries	(Sun, Ye et al. 2024)
Analyzed flow patterns with drill pipe rotation, enhancing cuttings removal.	Numerical investigation	Rotation speed, velocity, flow patterns	Neglects high-pressure effects	(van Deurzen 2024)
Sweeping pills improve cuttings removal in turbulent flow.	CFD modeling	Fluid rheology, power capacity	Validation in field conditions needed	(Aliyeva, Czuprat et al. 2024)
Reviewed multiphase challenges, emphasizing transport improvements.	Literature review	Flow regimes, particle interactions	Lack of real-time integration	(Obi, Hasan et al. 2024)
Transient two-phase flow for blocky cuttings in shale gas wells.	Experimental study	Momentum exchange, particle size	Scalability to diverse wells	(Chen, Li et al. 2025)
Optimized drill bit structure for better reverse circulation.	Two-phase flow simulation	Bit structure, process parameters	Needs broader parameter testing	(Qi, Cao et al. 2025)
Novel hole cleaning tool improves transport via swirling jets.	Multi-objective optimization	Flow rates, tool design	Cost-effectiveness in practice	(Hu, Zhang et al. 2025)

(Table 2) critically highlights how recent CFD and experimental approaches address transport efficiency, but gaps in field validation and scalability persist, underscoring the need for hybrid models.

2.2. Research Trend Review

The evolution of multiphase flow research in drilling and production systems over the past decade demonstrates a clear transition from fundamental theoretical exploration toward

data-driven modeling, real-time optimization, and sustainable engineering practices. This progression reflects the industry's response to increasingly complex wellbore geometries, environmental constraints, and the demand for operational efficiency and automation.

During the early development phase (2010-2015), research efforts primarily concentrated on establishing a theoretical and phenomenological understanding of multiphase flow dynamics within annular

and non-Newtonian fluid environments. These studies focused on characterizing phase interactions, particle settling behavior, and hydrodynamic stability, laying the groundwork for more sophisticated modeling approaches (Ikram, Mohamed Jan et al. 2021). The introduction of Computational Fluid Dynamics (CFD) into drilling research marked a turning point, enabling the visualization and quantification of cuttings transport phenomena under controlled conditions (Guo, Cheng et al. 2024). However, the early applications were largely constrained to laboratory or simulated environments, with limited field validation and poor scalability to real-world drilling operations due to computational and instrumentation limitations (Ikram, Jan et al. 2022).

The technological integration phase (2016-2020) witnessed the widespread adoption of hybrid numerical approaches, particularly the coupling of CFD and Discrete Element Method (DEM) models to capture particle-fluid interactions with greater fidelity. These methods enhanced predictive accuracy for cuttings migration, bed formation, and suspension stability, providing new insights into wellbore hydraulics and cleaning efficiency. Parallel to these developments, the design of advanced drilling fluids with tailored rheological and viscoelastic properties became a focal research area, addressing the challenges of non-Newtonian behavior, yield stress control, and shear-thinning optimization for efficient cuttings transport (Guo, Cheng et al. 2024). Concurrently, environmental awareness began to shape research priorities, with an increased emphasis on waste management, toxicity reduction, and fluid recyclability in line with emerging global sustainability standards (Huang, Lv et al. 2023).

2021-Present: Innovations and Sustainability.

In the modern innovation phase (2021-present), the field has entered a new paradigm characterized by digitalization,

automation, and sustainability. The integration of real-time monitoring systems, sensor-driven feedback loops, and AI-assisted predictive models has transformed multiphase flow management from reactive to proactive control (Swasdisevi, Thiangoen et al. 2024). These technologies enable real-time prediction of flow instabilities, dynamic optimization of pump rates, and early detection of cuttings bed accumulation, significantly enhancing safety and reducing non-productive time (NPT). Moreover, the growing commitment to sustainable drilling practices has led to the introduction of biodegradable drilling fluids, nanostructured additives, and waste recycling systems, aligning operational efficiency with environmental responsibility (Huang, Lv et al. 2023, Ali, Gailani et al. 2024).

Most recently, research trends in 2024 and beyond have emphasized AI-driven optimization frameworks, employing deep learning and adaptive hybrid models to improve the accuracy of multiphase flow prediction in complex, dynamic environments. These models show promise for closed-loop control systems and autonomous drilling applications. However, critical challenges remain unresolved particularly in the areas of data privacy, model generalizability, and robustness under uncertain geological conditions. Bridging these gaps requires the development of integrated digital twins, combining physics-based and data-driven modeling to ensure both predictive reliability and operational transparency.

2.3. Multiphase Flow in Annular Wells: Challenges and Effectiveness

Multiphase flow in annular wells introduces complexities not present in straight or vertical wellbore geometries. In large-diameter annuli, secondary vortices and uneven velocity distributions increase the risk of cuttings bed formation, with accumulation reported at 30-50% of the annular cross-sectional area when

annular velocity falls below 1.0 m/s (Rasul, Qureshi et al. 2020, Zhu, Huang et al. 2020). Compared to straight horizontal sections, annular wells experience stronger gravitational segregation of cuttings, particularly at low inclination angles (30-60°), which reduces transport efficiency by 20-25% under identical flow rates (Awad, Hussein et al. 2022).

Recent CFD-DEM simulations highlight that annular eccentricity exacerbates cuttings settling, requiring annular velocities at least 1.2-1.5 m/s to maintain suspension (Liu, Zhang et al. 2021). Experimental studies further show that pipe rotation can reduce cuttings bed thickness by 15-20%, but only under moderate rotation speeds (<120 RPM), as excessive speeds may destabilize flow regimes (van Deurzen 2024).

Despite these advances, significant research gaps remain. Few studies have quantified annular flow efficiency under HPHT (high-pressure, high-temperature) conditions, and scaling laboratory results to ultra-deep or extended-reach wells remains a challenge. For instance, full-scale CFD-DEM simulations for a 5000 m ultra-deep well segment may require up to 1000 CPU hours and 50-100 GB of memory, making routine application impractical without access to supercomputing infrastructure (Awad, Hussein et al. 2022). Additionally, the long-term environmental consequences of poor annular transport, such as increased discharge volumes, are underexplored. These gaps underline the importance of this review's synthesis in connecting multiphase flow fundamentals with applied solutions in annular wellbore conditions.

2.4. Modeling Process and Governing Equations

The modeling of multiphase flow in drilling operations provides a quantitative foundation for understanding how gas, liquid, and solid phases interact during cuttings transport. Although the modeling approaches vary

depending on well geometry and fluid type, most studies rely on the fundamental principles of mass, momentum, and energy conservation to describe the behavior of each phase and their mutual coupling. At the core of multiphase flow modeling are the continuity and momentum equations that express the conservation of mass and momentum within the fluid domain. These equations account for the spatial and temporal variations of density, velocity, and pressure and form the basis for computational fluid dynamics (CFD) simulations widely used in recent research. The continuity equation ensures that the total mass of the mixture remains constant, while the momentum equation balances the inertial, viscous, pressure, and gravitational forces acting within the flow (Awad, Hussein et al. 2022).

To represent the influence of solid particles (cuttings) suspended in the drilling fluid, additional terms are introduced to model interphase interactions, such as drag, lift, and buoyancy forces. These forces govern how particles accelerate, settle, or remain suspended depending on flow velocity, particle size, and fluid rheology. In some advanced studies, the Discrete Element Method (DEM) is coupled with CFD to explicitly resolve particle trajectories and collisions, providing deeper insights into bed formation and particle dispersion patterns. For turbulent multiphase systems, Reynolds-Averaged Navier-Stokes (RANS) models combined with turbulence closures such as the $k-\varepsilon$ or $k-\omega$ formulations are commonly applied to capture the effect of fluctuating velocities and pressure gradients. These models are particularly effective for predicting cuttings transport efficiency and pressure drop in non-Newtonian drilling fluids (Guo, Cheng et al. 2024).

When non-Newtonian fluids are used, the constitutive relationship between shear stress and shear rate is typically represented by the Herschel-Bulkley or power-law models, allowing rheological parameters such as yield stress and flow index to be incorporated into

the governing equations. This provides realistic predictions of fluid viscosity and carrying capacity under different shear conditions. Boundary conditions play a crucial role in defining the simulation environment. The no-slip condition at the wellbore wall, specified velocity or pressure at the inlet, and outflow or fixed pressure at the outlet are standard assumptions that determine flow stability and convergence. In inclined or horizontal wells, gravitational components and secondary flow effects are included to reproduce the complex circulation patterns observed in annular geometries (Rasul, Qureshi et al. 2020).

3. Key Concepts and Mechanisms

3.1. Fundamental Concepts of Multiphase Flow in the Drilling Environment

A comprehensive understanding of the multiphase flow mechanisms within the drilling environment is fundamental to ensuring operational efficiency, wellbore stability, and safety. In drilling hydraulics, the flow typically consists of three interacting phases gas, liquid, and solid whose dynamic interplay dictates pressure behavior, cuttings transport efficiency, and overall drilling performance.

The gas phase plays a critical role in pressure regulation and well control. Gas entrainment or gas influxes, if improperly managed, can induce severe pressure anomalies, leading to hazardous events such as kick formations or blowouts, particularly in underbalanced or depleted reservoirs. Therefore, understanding gas compressibility and transient gas migration within the annulus is essential for accurate pressure management and kick detection.

The liquid phase, primarily represented by drilling mud, serves as the primary carrier medium responsible for cuttings suspension, lubrication, and pressure stabilization within the wellbore. The effectiveness of this phase depends strongly on its rheological properties

including yield stress, viscosity, and shear-thinning behavior which govern the flow regime and cuttings carrying capacity. Any deviation from the designed rheological profile, whether due to temperature fluctuations, contamination, or improper fluid conditioning, can result in inefficient hole cleaning, barite sag, or excessive equivalent circulating density (ECD), thereby compromising drilling efficiency and structural stability.

The solid phase, comprising drill cuttings and entrained particulates, introduces significant challenges to flow behavior and wellbore integrity. Cuttings accumulation on the low side of horizontal and deviated wells can lead to cuttings bed formation, reduced annular flow area, and elevated torque and drag. Furthermore, high-velocity particle impingement can accelerate erosion of downhole tools, bit nozzles, and casing surfaces, leading to premature equipment degradation and increased operational costs (Geng, Zhang et al. 2023).

3.2. Challenges in Transporting Drill Cuttings and Implications for Drilling Operations

Drilling operations are inherently complex, and the behavior of multiphase flow within the wellbore introduces a series of interdependent challenges that directly affect safety, cost efficiency, and environmental performance.

One of the most critical issues is wellbore stability, where the accumulation of cuttings or improper pressure management can lead to formation collapse, stuck pipe, or loss of well integrity. Such instability not only disrupts drilling progress but also elevates non-productive time (NPT) and remediation costs. Equally significant are circulation losses, often caused by excessive annular pressure or fractures induced by high equivalent circulating density (ECD).

These losses increase operational expenditure

due to fluid replacement, lost materials, and downtime, while also complicating pressure control and reservoir management. Effective mitigation of circulation losses requires precise control of rheological parameters, real-time monitoring, and the adoption of intelligent drilling fluid systems capable of adapting to changing subsurface conditions.

Another vital aspect is hole cleaning efficiency, which ensures the continuous removal of drilled cuttings to prevent blockages, excessive torque and drag, or differential sticking. Inadequate hole cleaning compromises drilling performance, accelerates bit wear, and leads to deviations from the planned well trajectory. Similarly, erosion and mechanical wear resulting from the high-velocity impact of cuttings and fluid particulates pose substantial challenges to tool longevity and maintenance schedules. The cumulative effects of erosion can damage drill bits, casing, and surface equipment, necessitating costly replacements and frequent maintenance interventions (Sanei, Ardakani et al. 2020).

3.3. Flow Regimes and Their Implications for Drill Cuttings Transport

The efficiency of drilling operations is strongly influenced by the prevailing flow regime in the wellbore, which governs how fluids and solids are transported. Flow regimes determine suspension capacity, erosion potential, and risk of cuttings bed formation.

Bubbly flow occurs when small gas bubbles are dispersed in the liquid. It generally provides stable transport for fine particles but is limited for larger cuttings. Efficiency improvements are typically <10% over stratified flow, and degassers are required to prevent bubble accumulation.

Slug flow features alternating liquid and gas slugs, which improve mixing and cuttings suspension. Studies show it enhances transport efficiency by 15-20% compared to bubbly flow,

though pressure surges may increase erosion risks.

Annular flow is characterized by a liquid film along the pipe wall with a central gas core. It is highly effective for fine particle suspension, with efficiency gains of 2-35% compared to slug flow under high Reynolds number conditions. However, continuous liquid film erosion necessitates wear-resistant materials.

Churn flow is chaotic and unstable, with rapid regime transitions. Transport efficiency is difficult to predict but can fluctuate by $\pm 25\%$, causing operational instability. CFD-based modeling has been used to mitigate these fluctuations by providing early-warning.

Stratified flow occurs when fluids form distinct layers, with solids often settling at the lower boundary. This regime can reduce cuttings transport capacity by 40-60%, requiring agitation or inclined wellbores to restore flow efficiency.

Quantitative comparisons indicate that annular flow is generally the most favorable regime for maintaining suspension in high-velocity drilling operations, while stratified flow poses the greatest risks for blockages. (Figure 3) illustrates these regimes, and (Table 3) summarizes their efficiency ranges, implications, and management techniques.

By understanding these, engineers can optimize parameters. (Figure 3) shows flow regimes in a horizontal pipe, with colored patterns (e.g., blue for bubbly, red for slug) for clarity, illustrating transitions that affect transport efficiency predictions (Liu, Zhou et al. 2023, Shi, Wang et al. 2024). This figure emphasizes how regime shifts can lead to inefficiencies, a gap in current predictive models.

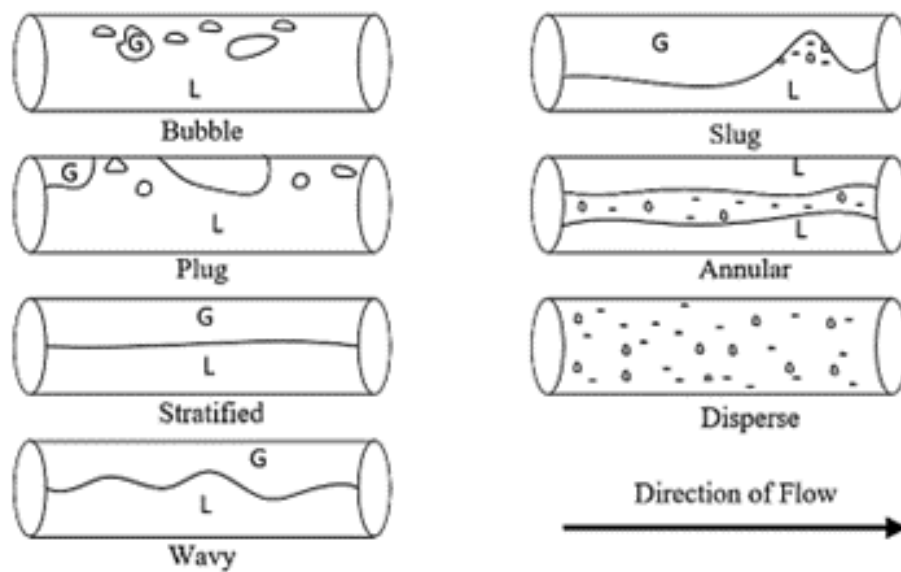


Figure 3. Flow regimes for gas-liquid two-phase flow in a horizontal pipe. The diagram illustrates transitions between bubbly (blue), slug (red), annular (green), churn (orange), and stratified (gray) flows. Color coding highlights regime-dependent transport efficiency, where annular flow offers the most stable particle suspension, while stratified flow leads to solids accumulation.

(Table 3) details flow regimes, their characteristics, and management techniques, showing how bubbly flow offers low erosion

but limited capacity, while churn flow poses instability risks [46-50].

Table 3. Flow Regimes and Their Implications for Drill Cuttings Transport

Flow Regime	Characteristics	Implications for Cuttings Transport	Challenges	Techniques/Equipment for Management	References
Bubbly Flow	Gas bubbles dispersed in liquid	Low erosion; limited for larger particles	Gas-liquid separation	Vacuum degassers; shakers	(Wijayanta, Catrawedarma et al. 2022)
Slug Flow	Alternating gas and liquid slugs	Moderate efficiency; good mixing	Pressure surges	Centrifuges; conditioners	(Barros, Rodrigues et al. 2022)
Annular Flow	Liquid film with gas core	Effective for small particles	Erosion	Wear-resistant materials	(Yaqub and Pendyala 2024)
Churn Flow	Chaotic with transitions	Difficult to predict	Instability	CFD; automated systems	(Davaranpanah and engineering 2024)
Stratified Flow	Distinct layers	Poor transport; solids settle	Accumulation	Inclined pipes; agitation	(Wijayanta, Catrawedarma et al. 2022)

4. Advanced Solid Control Technologies in Drilling Operations

Solid control systems are essential for removing particles from fluids (Pereira, Sad et al. 2022). Key technologies include shale shakers

(Nascentes, Murata et al. 2022), centrifuges, desanders/desilters, and vacuum degassers. (Table 4) compares the benefits, drawbacks, and performance metrics of various solid control technologies used in drilling operations.

Table4. Advantages, Disadvantages, and Comparison of Solid Control Technologies

Technology	Advantages	Limitations	Cost Efficiency	Particle Size Handled	Environmental Benefits	References
Shale Shakers	Ideal for primary cuttings; easy maintenance; minimizes fluid loss	Limited to smaller particles; screen blinding; needs monitoring	Low	High (Large)	Reduces waste	(Ghaniyari Benis , Korostelkin, Filintsev et al. 2020)
Centrifuges	Removes small particles; reduces mud weight; handles large volumes	High costs; skilled maintenance; limited for large cuttings	High Initial	Very High (Fine)	Maximum fluid recovery	(Awad, Hussein et al. 2022, Pereira, Sad et al. 2022)
Desanders/Desilters	Removes sand/silt; improves stability; protects equipment	Less effective on small particles; high energy; prone to blockage	Moderate	Moderate (Sand/Silt)	Protects downstream equipment	(Islam and Hos-sain 2020, Yang, Wang et al. 2024)
Vacuum Degassers	Removes gas; prevents pump lock; enhances efficiency	Ongoing monitoring; high investment; less effective in high-gas	Moderate	N/A (Gas)	Improves fluid properties	(Patel and Santra 2020)

5. Innovations Revolutionizing Multiphase Flow in Oil and Gas

Recent innovations have transformed multiphase flow management by improving operational efficiency, sustainability, and safety. Among these, real-time monitoring systems have shown the most immediate impact, reducing downtime by 25-30% in North Sea offshore rigs through early anomaly detection (Nygård, Andreassen et al. 2021). Advanced CFD and DEM models improve predictive accuracy of flow behavior by 15-20% compared to conventional correlations, enabling better parameter optimization in deepwater drilling. However, scaling these models to full-field or ultra-deep wells demands extensive computational power, often exceeding 500 CPU cores for a single simulation run, which constrains field deployment (Awad, Hussein et al. 2022, Wang, Animasaun et al. 2024).

Automated control systems, often driven by AI, minimize human error by ~35%, though their adoption faces barriers due to high initial costs and cybersecurity risks. Biodegradable drilling fluids provide substantial environmental

benefits, reducing ecological footprint by 35-40% in European onshore field trials, but face 20-40% higher costs compared to conventional muds, limiting large-scale deployment. Encapsulation techniques for hazardous cuttings show promise in fragile ecosystems such as Arctic offshore, reducing leak risks by more than 50%, though their operational costs remain high (Cherepovitsyn, Lebedev et al. 2023).

These evaluations indicate that while all innovations contribute to sustainability and safety, real-time monitoring and advanced CFD models currently offer the strongest balance between efficiency gains and cost-effectiveness.

Key innovations: Advanced separation, real-time monitoring, automated controls, encapsulation, computational models (Ali, Abdul-Majeed et al. 2025).

5.1. Robotics-Based Systems for Drill Cuttings Handling

Robotics-based systems are emerging as a complementary innovation in drill cuttings management, particularly in offshore environments where personnel exposure to hazardous conditions poses a significant safety

challenge. These systems include robotic arms, automated conveyors, and remotely operated vehicles (ROVs) designed to transport and process cuttings with minimal human intervention.

Field trials in offshore rigs have shown that robotic cuttings handling can reduce manual exposure to hazardous zones by 40-50%, substantially improving worker safety. In addition, autonomous robotic conveyors have been reported to improve material transfer efficiency by 20-25% compared to conventional manual systems, particularly under high-load drilling operations.

Beyond safety, robotics also contribute to operational efficiency. Integrated robotic platforms can operate continuously without fatigue, leading to reductions in handling time of 15-20% per drilling cycle. When combined with automated monitoring, these systems enhance reliability by reducing unplanned shutdowns linked to human error. Despite these benefits, the adoption of robotics remains limited due to high capital costs and the complexity of integrating robotic units into existing rig infrastructure. Current deployments

are largely confined to high-risk offshore projects, where safety gains justify investment. Wider adoption will require cost reductions, standardized robotic interfaces, and long-term field validation in both offshore and onshore environments (Alimi, Jin et al. 2025).

(Figure 4) Illustrates the transformation of drill cuttings management from manual to automated workflows. The traditional process (left) relies on manual cuttings handling, discrete monitoring, and reactive adjustments following flow anomalies, often resulting in higher downtime and elevated worker exposure. In contrast, the automated process (right) employs robotics-assisted handling combined with AI-based real-time monitoring and proactive control loops, minimizing human intervention and enabling continuous optimization. Field implementations have demonstrated up to 40-50% reductions in worker exposure, 25-30% decreases in downtime, and 35-40% improvements in environmental performance, highlighting the operational, safety, and sustainability benefits of automation in modern drilling environments.

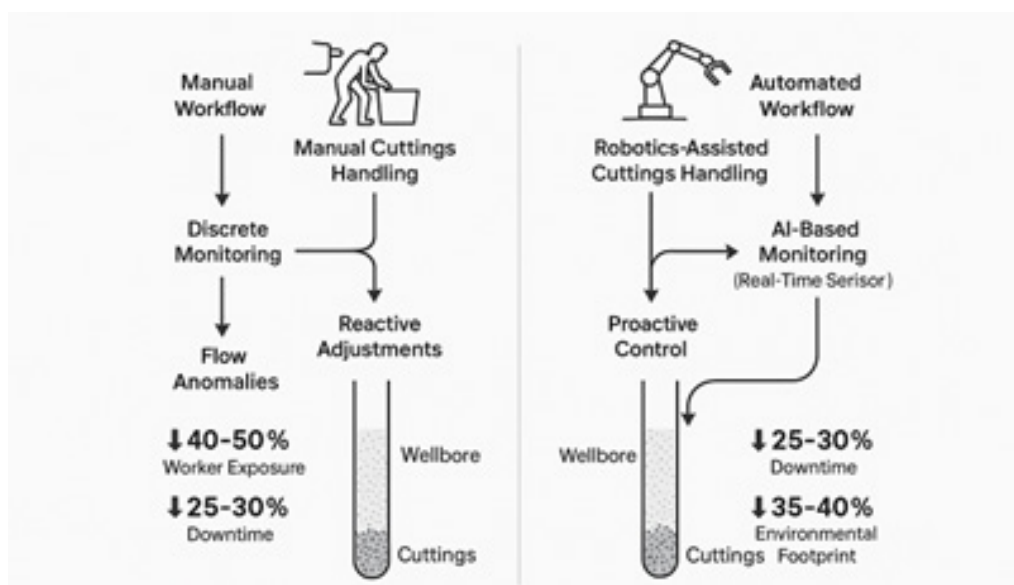


Figure 4. Comparative Workflow of Traditional vs. Automated Cuttings Handling Systems.

(Table 5) highlights the effects and implications of recent technological advancements on the

efficiency and effectiveness of drill cuttings transport.

Table 5. Quantitative Impact of Recent Innovations in Drill Cuttings Transport

Innovation	Key Features	Quantitative Impact on Operations	Challenges/Limitations	Example Applications	References
Real-Time Monitoring	Continuous tracking of flow, pressure, and cuttings concentration	Downtime reduction of 25-30% through early anomaly detection	High costs; requires skilled personnel	North Sea offshore rigs	(Nygård, Andreassen et al. 2021)
Advanced CFD Models	High-fidelity simulations of multiphase flow behavior	Predictive accuracy improvement of 15-20% compared to conventional correlations	Computationally intensive; scaling to ultra-deep wells requires high-performance computing (HPC) clusters with >500 CPU cores and simulation runtimes exceeding 72-120 hours, limiting field applicability	Deepwater Gulf of Mexico	(Awad, Hussein et al. 2022, Wang, Animasaun et al. 2024)
Automated Control (AI)	AI-driven adjustments of flow parameters	Reduction of human error by ~35%; improved safety margins	Resistance to adoption; cybersecurity risks	Offshore Canada drilling	(Sircar, Yadav et al. 2021)
Biodegradable Fluids	Eco-friendly rheology tailored for drilling	Reduction in environmental emissions by 35-40%; compliance with EU regulations	Costs 20-40% higher than conventional muds	European onshore wells	(Razali, Yunus et al. 2018)
Encapsulation Methods	Encapsulation of hazardous cuttings for disposal	Reduction in leakage/spillage risks by ~%50 in Arctic operations	Material availability; high operational costs	Arctic offshore drilling	(Cherepovitsyn, Lebedev et al. 2023)

5.2. Nanotechnology Applications in Multiphase Flow; Drill Cuttings Transport

Nanotechnology has emerged as a transformative approach in drilling engineering, offering unique opportunities to enhance the performance of drilling fluids, optimize multiphase flow behavior, and improve environmental sustainability.

The incorporation of nanoparticles (NPs) into drilling fluids can modify their rheological and thermal properties, leading to superior cuttings transport and wellbore stability, particularly under high-pressure, high-temperature (HPHT) conditions. Nanoparticles such as SiO_2 , Al_2O_3 , ZnO , TiO_2 , and graphene-based materials have been shown to improve lubrication, thermal conductivity, and yield stress control, thereby

reducing torque, drag, and differential sticking (Sun, Ye et al. 2024).

Their high surface area-to-volume ratio enhances particle dispersion and suspension stability, leading to a 10-20% improvement in cuttings transport efficiency compared to conventional fluids. Additionally, nanobiodegradable drilling fluids developed using green synthesis methods have demonstrated 25-35% reductions in fluid loss and environmental toxicity (Ali, Gailani et al. 2024).

From a multiphase flow perspective, nanomaterials facilitate better solid-liquid-gas interaction control, improving interface stability and reducing phase segregation. In CFD-DEM simulations, nano-additives improve predictive accuracy for drag coefficients and slip velocity, especially in turbulent and annular

flow regimes (Guo, Cheng et al. 2024). The use of nanoparticle-stabilized foams further enhances gas-liquid interface stability, providing improved hole cleaning in underbalanced drilling scenarios.

Environmentally, nanotechnology enables waste reduction and fluid recyclability by enhancing the reusability of drilling muds and minimizing the release of toxic additives. Recent studies report that nano-enhanced fluids not only meet but exceed API standards for biodegradability and thermal stability (Fan, Zhuang et al. 2025). Despite these advantages, challenges such as nanoparticle agglomeration, cost of synthesis, and long-term environmental impact remain active research areas. Future

work should focus on the scalability of green nanomaterial production, the development of hybrid nano-polymer fluids, and integration with AI-driven monitoring systems for real-time optimization of drilling performance (Ali, Gailani et al. 2024).

6. Environmental Impact and Sustainability

Improper handling leads to contamination (George, Nawawi et al. 2024). Mitigation via biodegradable fluids, recycling (Ikram, Jan et al. 2022). (Table 6) assesses the environmental consequences and sustainability aspects of different methods employed for drill cuttings transport.

Table 6. Environmental Impact of Drill Cuttings Transport Methods

Innovation	Key Feature	Environmental Benefit	Challenges	Application	References
Thermal Desorption Units	Reduces hydrocarbons	Hydrocarbon recovery	High energy	Offshore rigs	(Liu, Li et al. 2019)
Recycling and Reuse	Minimizes disposal	Circular economy	Logistics costs	North Sea construction	(Kazamias and Zorpas 2021)
Subsurface Injection	Eliminates surface waste	Safe in formations	Geological assessments	Gulf of Mexico	(Parashar, Thakur et al. 2024)
Biodegradable Fluids	Minimal harm	Regulatory alignment	Initial costs	European projects	(Razali, Yunus et al. 2018)
Encapsulation Methods	Contains hazards	Reduces leaks	Material availability	Arctic drilling	(Pereira, Sad et al. 2022)

6.1. Regulations, Standards, and Sustainability Driving Technological Adoption

Regulatory frameworks drive adoption (Okeke and Indicators 2021). Standards from API/ISO (Nwakile, Hanson et al. 2023). Initiatives include AI monitoring (Cherepovitsyn, Rutenko et al. 2021). Critically, while regulations push

sustainability, enforcement gaps in emerging markets hinder progress.

7. Case Studies

(Table 7) presents real-world examples and outcomes from various case studies related to drill cuttings transport across different operational contexts.

Table 7. Case Studies in Drill Cuttings Transport

Case Study	Location	Outcomes	Challenges	Lessons Learned	References
Real-Time Monitoring Offshore	North Sea	30% downtime reduction	Investment/training	Enhances efficiency/safety	(Nygård, Andreassen et al. 2021)
CFD for Deepwater	Gulf of Mexico	Optimized fluids	Computational cost	Essential for complex regimes	(Cuamatzi-Meléndez, Tetlalmatzin-García et al. 2023)
Recycling for Construction	Onshore Norway	Reduced costs/impact	Logistics	Dual benefits	(Innes, Nesse et al. 2021)
Biodegradable Fluids Onshore	Germany	Regulatory compliance	Fluid costs	Viable for sensitive ops	(Olry, Cascone et al. 2024)
Thermal Desorption Units	Middle East	Hydrocarbon recovery	Energy/complexity	Effective for hazardous waste	(Li, Kameyama et al. 2020)
Subsurface Injection	Gulf of Thailand	No surface waste	Formations suitability	Ideal for strict regs	(Cuamatzi-Meléndez, Tetlalmatzin-García et al. 2023)
Encapsulation Arctic	Canada	No leaks	Costs/materials	Effective in fragile ecosystems	(Cherepovitsyn, Lebedev et al. 2023)

These cases demonstrate practical applications, but highlight cost and site-specific challenges.

8. The Future of Multiphase Flow Management: A Sustainable Outlook

Trends: Advanced separation, sensors, AI, green tech, modeling, CCU, collaboration.

Future holds efficiency gains (Alizadeh, Khalili et al. 2024, Qiu, Zhou et al. 2024, Saxena, Prakash Gupta et al. 2024). (Table 8) forecasts advancements.

Table 8. Forecasting Potential Advancements in Multiphase Flow Technology

Technology	Key Features	Expected Benefits	Challenges	Examples	References
Artificial Intelligence	Predictive modeling	Optimized efficiency	Data needs	Offshore automation	(Wang 2017)
Green Drilling	Biodegradable/low-emission	Reduced footprint	Costs/scalability	Sensitive projects	(Wang, Ge et al. 2017)
Smart Sensors	Real-time monitoring	Precision	Integration	Arctic/deepwater	(Wang, Ge et al. 2017)
Advanced CFD/DEM	Simulations	Accurate predictions	Computational	Ultra-deep wells	(Lahey Jr, Baglietto et al. 2021)
CCU	CO ₂ capture/reuse	Neutrality	Infrastructure	Multiphase systems	(Lau, Ramakrishna et al. 2021)
Robotics/Automation	Autonomous transport	Safety/precision	Development costs	Hazardous rigs	(Chen, Stavinoha et al. 2014)
Hybrid Energy	Renewables integration	Lower costs	Intermittency	Remote drilling	(Tee, Tan et al. 2019)

8.1. The Role of AI in Drilling Operations

AI is transforming drilling by optimizing operations, predicting failures, and enhancing safety. Key applications include geo-steering, site identification, production enhancement, and well placement. For instance, AI reduces risks in high-stakes environments and boosts efficiencies (Noshi and Schubert 2018).

Critically, AI addresses multiphase flow gaps by analyzing real-time data for better cuttings transport, but challenges include data quality and ethical concerns. In addition, the integration of AI-driven real-time monitoring systems

introduces significant cybersecurity and data privacy challenges. Sensitive operational data such as wellbore pressure, flow rates, and drilling parameters can be vulnerable to data breaches or unauthorized access during cloud-based data transmission, potentially compromising both safety and proprietary information (Sircar, Yadav et al. 2021, Aderamo, Olisakwe et al. 2024).

Strengthening encryption protocols and implementing secure data governance frameworks are therefore critical to ensure trustworthy AI deployment in drilling operations. (Table 9) summarizes AI advancements.

Table 9. AI Applications in Drilling Operations

Application	Description	Benefits	Challenges	References
Geo-steering	AI-driven path optimization	Efficiency, reduced footprint	Integration costs	(Muhammad, Cheraghi et al. 2024)
Exploration	Data analysis for sites	Accuracy, cost savings	Data volume	(Dada, Oliha et al. 2024)
Predictive Maintenance	Failure prediction	Downtime reduction	Algorithm accuracy	(Hanif and Research 2024)
Automation	Robotic drilling	Safety, precision	Adoption barriers	(Ohalete, Aderibigbe et al. 2023)
Supply Chain	Logistics optimization	Efficiency	Cybersecurity	(John, Oyeyemi et al. 2022)

This section highlights AI's potential to fill research gaps in predictive modeling.

8.2. AI-Based Stimulation Workflows

AI-based stimulation workflows represent a paradigm shift from conventional, empirically guided operations toward data-centric, adaptive, and autonomous decision-making. By integrating historical field data, real-time sensor inputs (e.g., SCADA, DAS, DTS), and machine learning models, these workflows continuously refine stimulation design and execution parameters (Khan, Barooah et al. 2023).

At the design stage, hybrid models such as CFD-DEM simulations combined with AI algorithms (e.g., Gradient Boosting, Reinforcement Learning)

enable optimized fluid compositions, proppant schedules, and acid placement strategies. During execution, real-time data streams from pressure and acoustic sensors are processed by AI-based control systems that autonomously adjust pumping rates, fluid viscosity, and injection timing to maintain operational stability (Xu, Song et al. 2025).

Post-treatment evaluation is further enhanced through AI-assisted production forecasting and anomaly detection, allowing for continuous improvement in subsequent jobs. Collectively, these adaptive frameworks not only increase stimulation efficiency and reliability but also align with ESG and sustainability objectives by minimizing resource consumption and operational risks.

(Figure 5) represent the integrated AI-driven workflow combining sensor data acquisition, CFD-DEM simulation, and automated control for intelligent well stimulation. The feedback-

enabled system continuously analyzes field data to optimize operational parameters and ensure efficient, safe, and sustainable performance.

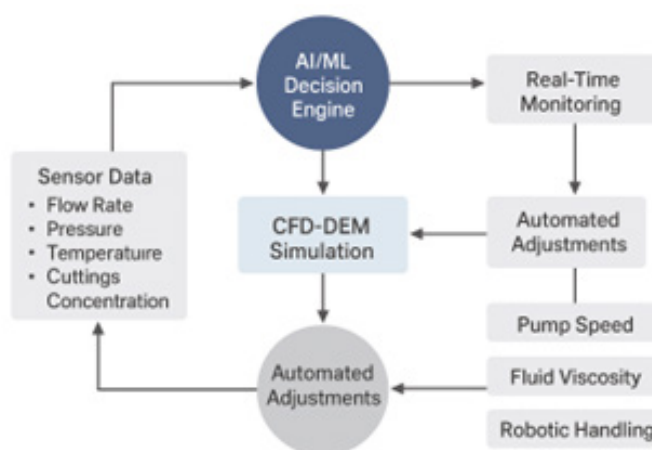


Figure 5. Integrated Multiphase Flow and Automation Framework for Drill Cuttings Transport generate this figure.

8.3. Comparison of Offshore vs. Onshore Applications

Offshore drill cuttings transport faces unique challenges compared to onshore, including higher costs, logistical complexities, and environmental risks. Offshore often uses thermal treatment or subsurface injection due to space limits, while onshore favors recycling and land-based disposal (Ochulor, Sofoluwe et al. 2024). Key differences:

1. Cost: Offshore 2-3x higher due to transport distances.
2. Technology: Offshore relies on compact systems like CTS; onshore uses larger shakers/centrifuges.
3. Environmental Impact: Offshore risks marine pollution; onshore soil contamination.
4. Efficiency: Onshore simpler logistics; offshore needs advanced monitoring for waves/weather.

Critically, offshore scalability is limited by regulations, while onshore benefits from easier waste reuse.

9. Conclusions

The findings of this review reinforce the critical importance of data-driven, sustainable, and automated approaches in advancing multiphase flow management for drilling operations. The integration of CFD-assisted simulation with real-time sensing has proven effective in optimizing hydraulic parameters, reducing downtime, and enhancing cuttings transport efficiency. However, large-scale industrial implementation requires addressing several challenges, including standardization of nanofluid formulations, interoperability between sensor and AI systems, and validation of hybrid CFD-DEM-AI models under diverse field conditions.

For practical deployment, future drilling systems should adopt a modular architecture that combines physics-based simulation, AI-enabled control, and robotic handling into a single closed-loop automation environment. Establishing industry-wide data standards for environmental monitoring, waste recycling, and energy optimization will facilitate interoperability and accelerate technology transfer from laboratory to field operations.

Looking ahead, next-generation multiphase flow systems are expected to evolve into self-optimizing drilling platforms capable of autonomous learning and adaptive control. These systems will dynamically adjust operational parameters based on real-time data to maintain performance, minimize environmental impact, and uphold safety standards even under highly variable subsurface conditions. The convergence of physics-based modeling, sustainable materials engineering, and digital automation offers a tangible pathway toward a cleaner, safer, and economically resilient oil and gas industry.

To enhance the interpretability and visual clarity of these advancements, it is recommended that future studies incorporate schematic diagrams depicting:

1. The CFD-DEM coupling mechanism for multiphase flow simulation;
2. The sensor-AI feedback architecture for real-time control;
3. Comparative schematics of manual versus robotic cuttings handling workflows; and
4. A sustainability framework illustrating the interconnections among drilling fluid selection, waste management, and emission reduction.

References

- Aderamo, A. T., H. C. Olisakwe, Y. A. Adebayo, A. E. J. C. R. Esiri, R. i. Engineering and Technology (2024). "AI-enabled predictive safeguards for offshore oil facilities: Enhancing safety and operational efficiency." 2(1): 23-43.
- Ali, A. A., G. H. Abdul-Majeed, A. J. A. J. f. S. Al-Sarkhi and Engineering (2025). "Review of multiphase flow models in the petroleum engineering: Classifications, simulator types, and applications." 50(7): 4413-4456.
- Ali, J. A., R. Gailani, A. D. Abdullah, P. T. Jaf, S. M. Simo, M. Abdalqadir, V. M. J. E. S. Faris and P. Research (2024). "Performance evaluation of the nano-biodegradable drilling fluid using the greenly synthesized zinc nanorods and gundelia seed waste." 31(39): 51381-51400.
- Alimi, K., R. Jin, B. N. Nguyen, Q. Nguyen, W. Chen, L. J. J. o. S. Hosking and T. Technology (2025). "Exploring artificial intelligence applications in construction and demolition waste management: a review of existing literature." 104-136.
- Aliyeva, T., O. Czuprat and P. Byrski.(2024). CFD modelling of multiphase flow in horizontal pipe annulus: Effect of sweeping pills on drill cuttings removal. SPE Annual Technical Conference and Exhibition?, SPE.
- Alizadeh, S. M., Y. Khalili and M. J. E. Ahmadi (2024). "Comprehensive review of carbon capture and storage integration in hydrogen production: opportunities, challenges, and future perspectives." 17(21): 5330.
- Awad, A. M., I. A. Hussein, M. S. Nasser, S. A. Ghani, A. O. J. J. o. P. S. Mahgoub and Engineering (2022). "A CFD-RSM study of cuttings transport in non-Newtonian drilling fluids: Impact of operational parameters." 208: 109613.
- Barros, H. A., R. L. Rodrigues, R. F. Alves, C. Cozin, H. T. Rodrigues, R. da Fonseca Junior, M. J. da Silva, M. A. M. Neto, R. E. J. E. T. Morales and F. Science (2022). "Experimental slug flow dissipation analysis in pipes with horizontal to inclined downward direction change." 139: 110740.
- Chen, H., S. Stavinoha, M. Walker, B. Zhang, T. A. J. I. C. Fuhlbrigg and Automation (2014). "Opportunities and Challenges of Robotics and Automation in Offshore Oil & Gas Industry." 5: 136-145.
- Chen, Y., W. Li, X. Wang, J. Guo, P. Wu, Z. Yang and H. J. F. Yang (2025). "Experimental Investigation of the Effects of Blocky Cuttings Transport on Drag and Drive Torque in Horizontal Wells." 10(9): 219.
- Cherepovitsyn, A., A. J. J. o. M. S. Lebedev and Engineering (2023). "Drill cuttings disposal efficiency in offshore oil drilling." 11(2): 317.
- Cherepovitsyn, A., E. Rutenko, V. J. J. o. M. S. Solovyova and Engineering (2021). "Sustainable

- development of oil and gas resources: A system of environmental, socio-economic, and innovation indicators." 9(11): 1307.
- Cochrane, S., S. Ekehaug, R. Pettersen, E. Refit, I. Hansen and L. J. M. p. b. Aas (2019). "Detection of deposited drill cuttings on the sea floor-A comparison between underwater hyperspectral imagery and the human eye." 145: 67-80.
- Costa, L., C. Carvalho, A. Soares, A. Souza, E. Bastos, E. Guimarães, J. Santos, T. Carvalho, V. Calderari and L. J. M. P. B. Marinho (2023). "Physical and chemical characterization of drill cuttings: A review." 194: 115342.
- Cuamatzi-Meléndez, R., S. Tetlalmatzin-García, S. D. Dionicio-Bravo, E. Flores-Cuamatzi, E. J. J. o. O. E. Aranda-López and M. Energy (2023). "Theoretical and CFD modelling of single and slug oil, water and gas flows in a deepwater rigid jumper." 9(4): 603-622.
- Dada, M. A., J. S. Oliha, M. T. Majemite, A. Obaigbena, P. W. J. E. S. Bui and T. Journal (2024). "A review of predictive analytics in the exploration and management of us geological resources." 5(2): 313-337.
- Davarpanah, A. J. A. s. c. and engineering (2024). "Comparative evaluation of carbon capture, utilization, and storage (CCUS) technologies using multi-criteria decision-making approaches." 12(25) :9498-9510.
- Deng, S., Y. Huang, X. Hu, H. Wang, H. Zhao and J. J. A. o. He (2022). "Nano-film-forming plugging drilling fluid and bridging cross-linking plugging agent are used to strengthen wellbores in complex formations." 7(26): 22804-22810.
- Epelle, E. I., D. I. J. C. E. R. Gerogiorgis and Design (2018). "Transient and steady state analysis of drill cuttings transport phenomena under turbulent conditions." 131: 520-544.
- Fan, W., G. Zhuang, Q. Li, P. Yuan, D. J. E. Liu and Fuels (2025). "Review of Nanoparticles in Water-Based Drilling Fluids: Innovations, Challenges, and Future Directions." 39(19): 8800-8826.
- Geng, Y., Z. Zhang, Z. Yan, Y. Yuan, X. Zhou, W. Yue and Y. J. R. a. An (2023). "A novel graphene/triolein complex-based lubricant for improving high temperature water-based drilling fluid." 13(49): 34772-34781.
- George, I. I., M. G. M. Nawawi, Z. J. Mohd, B. S. J. E. S. Farah and P. Research (2024). "Environmental effects from petroleum product transportation spillage in Nigeria: a critical review." 31(2): 1719-1747.
- Ghaniyari Benis, S. PERFORMANCE STUDY OF A BENCH SCALE SHALE SHAKER, University of Akron.
- Guo, L., H. Cheng, Z. Yao, C. Rong, Z. Wang and X. J. S. R. Wang (2024). "CFD-DEM method is used to study the multi-phase coupling slag discharge flow field of gas-lift reverse circulation in drilling shaft sinking." 14(1): 13853.
- Hajipour, M. J. S. A. S. (2020). "CFD simulation of turbulent flow of drill cuttings and parametric studies in a horizontal annulus." 2(6): 1146.
- Hanif, H. R. J. E. J. o. C., Medicinal and P. Research (2024). "The Role of Artificial Intelligence in Optimizing Oil Exploration and Production." 3(5): 176-190.
- Heydari, O., E. Sahraei, P. J. J. o. p. s. Skalle and engineering (2017). "Investigating the impact of drillpipe's rotation and eccentricity on cuttings transport phenomenon in various horizontal annuluses using computational fluid dynamics (CFD)." 156: 801-813.
- Hu, W., J. Zhang, N. Guan, H. J. G. S. Zhu and Engineering (2025). "Cuttings Transport Characteristics and Multi-Objective Optimization Design of a Novel Hole Cleaning Tool." 214053.
- Huang, N., K. Lv, J. Sun, J. Liu, J. Wang and Z. J. G. Wang (2023). "Study on the low-temperature rheology of polar drilling fluid and its regulation method." 9(2): 168.
- Hussein, I. A. and M. Mahmoud (2023). Fluid-Solid Interactions in Upstream Oil and Gas Applications, Elsevier.
- Ikram, R., B. M. Jan, W. Ahmad, A. Sidek, M. Khan

- and G. J. M. Kenanakis (2022). "Rheological investigation of welding waste-derived graphene oxide in water-based drilling fluids." 15(22): 8266.
- Ikram, R., B. Mohamed Jan, A. Sidek and G. J. M. Kenanakis (2021). "Utilization of eco-friendly waste generated nanomaterials in water-based drilling fluids; state of the art review." 14(15): 4171.
- Innes, G., S. Nesse and J. T. Eia (2021). A Comparative Emissions Assessment-Drill Cuttings Treatment Alternatives. Abu Dhabi International Petroleum Exhibition and Conference, SPE.
- Islam, M. R. and M. E. Hossain (2020). Drilling Engineering: Towards achieving total sustainability, Gulf Professional Publishing.
- John, A. O., B. B. J. I. J. o. M. R. Oyeyemi and G. Evaluation (2022). "The Role of AI in Oil and Gas Supply Chain Optimization." 3(1): 1075-1086.
- Kazamias, G. and A. A. J. J. o. C. P. Zorpas".(2021) Drill cuttings waste management from oil & gas exploitation industries through end-of-waste criteria in the framework of circular economy strategy." 322: 129098.
- Khan, M. S., A. Barooah, B. Lal and M. A. Rahman (2023). Multiphase Flow Systems and Potential of Machine Learning Approaches in Cutting Transport and Liquid Loading Scenarios. Machine Learning and Flow Assurance in Oil and Gas Production, Springer: 27-57.
- Kharazi Esfahani, P., M. Akbari and Y. J. S. R. Khalili (2024). "A comparative study of fracture conductivity prediction using ensemble methods in the acid fracturing treatment in oil wells." 14(1): 648.
- Kogbara, R. B., B. B. Dumkhana, J. M. Ayotamuno and R. N. J. C. Okparanma (2017). "Recycling stabilised/solidified drill cuttings for forage production in acidic soils." 184: 652-663.
- Korostelkin, A., A. Filintsev, V. Novokshonov and A. Nikitin (2020). On shale shaker's structural optimization and performance improvement. IOP Conference Series: Materials Science and Engineering, IOP Publishing.
- Lahey Jr, R. T., E. Baglietto, I. A. J. N. E. Bolotnov and Design (2021). "Progress in multiphase computational fluid dynamics." 374: 111018.
- Lau, H. C., S. Ramakrishna, K. Zhang, A. V. J. E. Radhamani and Fuels (2021). "The Role of Carbon Capture and Storage in the Energy Transition."
- Li, J.-L., S. Kameyama and G.-P. J. M. C. Yang (2020). "In-situ measurement of trace isoprene and dimethyl sulfide in seawater and oceanic atmosphere based on room temperature adsorption-thermal desorption." 222: 103787.
- Liu, G., W. Zhang, L. Zhang and J. J. M. Cheng (2021). "Theoretical prediction method for erosion damage of horizontal pipe by suspended particles in liquid-solid flows." 14(15): 4099.
- Liu, H., J. Li, M. Zhao, Y. Li and Y. J. C. Chen (2019). "Remediation of oil-based drill cuttings using low-temperature thermal desorption: Performance and kinetics modeling." 235: 1081-1088.
- Liu, Q., B. Zhou, F. Chen, N. Li, J. Xie, M. Zhao, Q. Di, C. Feng, S. Song and C. J. S. R. Yin (2023). "Optimal design and nonlinear dynamic characteristics of titanium/steel drill pipe composite drill string for ultra-deep drilling." 13(1): 20491.
- Mahmoud, A., R. Gajbhiye and S. J. S. R. Elkatatny (2024). "Investigating the efficacy of novel organoclay as a rheological additive for enhancing the performance of oil-based drilling fluids." 14(1): 5323.
- Mikos-Szymańska, M., P. Rusek, K. Borowik, M. Rolewicz, P. Bogusz, J. J. E. S. Gluzińska and P. Research (2018). "Characterization of drilling waste from shale gas exploration in Central and Eastern Poland." 25(36): 35990-36001.
- Muhammad, R. B., Y. Cheraghi, S. Alyaev, A. Srivastava and R. B. Bratvold (2024). Enhancing geosteering with AI: Integrating a decision-making robot into a cloud-based environment and benchmarking against human experts. SPE Norway Subsurface Conference, SPE.
- Nascentes, C. L., V. V. Murata, L. C. J. J. o. P. S. Oliveira-Lopes and Engineering (2022).

- "Mathematical modeling of solids-drilling fluid separation in shale shakers in oil fields: A state of art review." 208: 109270.
- Njuguna, J., S. Siddique, L. B. Kwroffie, S. Piromrat, K. Addae-Afoakwa, U. Ekeh-Adegbotolu, G. Oluyemi, K. Yates, A. K. Mishra and L. J. W. M. Moller (2022). "The fate of waste drilling fluids from oil & gas industry activities in the exploration and production operations." 139: 362-380.
- Noshi, C. I. and J. J. D. W. Schubert, October 10, (2018). "The Role of Machine Learning in Drilling Operations; A Review."
- Nwakile, C., E. Hanson, Y. Adebayo, A. J. G. J. o. A. R. Esiri and Reviews (2023). "A conceptual framework for sustainable energy practices in oil and gas operations." 1(02): 031-046.
- Nygård, B. E., E. Andreassen, J. A. Carlsen, G. Å. Ulfnes, S. Øksenvåg, R. Stabell, T. Davis, T. L. Naterstad, S. Zainoune and E. Vandvik (2021). Improved drilling operations with wired drill pipe and along-string measurements-learnings and highlights from multiple north sea deployments. SPE/IADC Drilling Conference and Exhibition, SPE.
- Obi, C., A. Hasan, A. Badejo, M. Rahman and D. J. P. Banerjee (2024). "Multiphase flow challenges in drilling, completions, and injection: Part 2." 10(4): 570-583.
- Ochulor, O. J., O. O. Sofoluwe, A. Ukato, D. D. J. W. J. o. A. R. Jambol and Reviews (2024). "Technological advancements in drilling: A comparative analysis of onshore and offshore applications." 22(2): 602-611.
- Ohalete, N. C., A. O. Aderibigbe, E. C. Ani, P. E. Ohenhen, A. J. W. J. o. A. R. Akinoso and Reviews (2023). "Advancements in predictive maintenance in the oil and gas industry: A review of AI and data science applications." 20(3): 167-181.
- Okeke, A. J. E. and S. Indicators (2021). "Towards sustainability in the global oil and gas industry: Identifying where the emphasis lies." 12: 100145.
- Olry, N., A. Cascone, M. Eils, L. Bussaglia and V. Smith (2024). Geothermal Drilling Fluid Meets Performance, Environmental, and Regulatory Challenges in the Alps. Proceedings of the 2024 AADE Fluids Technical Conference and Exhibition, American Association of Drilling Engineers.
- Parashar, V., C. J. I. o. p. w. o. e. p. Thakur and i. s. m. t. c. economy (2024). "Challenges, opportunities, and strategies for effective petroleum hydrocarbon waste management." 67-90.
- Patel, H. A. and A. J. S. r. Santra (2020). "Organically modified layered magnesium silicates to improve rheology of reservoir drilling fluids." 10(1): 13851.
- Pereira, L. B., C. M. Sad, E. V. Castro, P. R. Filgueiras and V. J. F. Lacerda Jr (2022). "Environmental impacts related to drilling fluid waste and treatment methods: A critical review." 310: 122301.
- Qi, B., Y. Cao, G. Cui, H. Liu, L. Zhai, P. Cao, J. J. G. S. Wu and Engineering (2025). "A Comprehensive Study on Evaluating Drainage Capability of Air Reverse Circulation Down-The-Hole Hammer Drill Bits via Numerical Simulation and Experimentation." 213918.
- Qiu, Z., L. Zhou, L. Bai, M. A. El-Emam, R. J. G. S. Agarwal and Engineering (2024). "Empirical and numerical advancements in gas-liquid separation technology: A review." 233: 212577.
- Rasul, G., M. F. Qureshi, H. Ferroudji, S. Butt, R. Hasan, I. Hassan, M. A. J. J. o. A. R. i. F. M. Rahman and T. Sciences (2020). "Analysis of cuttings transport and flow pattern in nearly horizontal extended reach well." 71(2): 69-86.
- Razali, S., R. Yunus, S. A. Rashid, H. Lim, B. M. J. R. Jan and S. E. Reviews (2018). "Review of biodegradable synthetic-based drilling fluid: Progression, performance and future prospect." 90: 171-186.
- Rodríguez-López, L. C., M. E. Ojeda-Morales, Y. Córdova-Bautista, M. A. Hernández-Rivera and J. J. J. o. E. M. de los Santos López-Lázaro (2021). "Recovery of impregnated hydrocarbon in drill

- cuttings using supercritical carbon dioxide." 285: 112134.
- Sanej, H., O. H. Ardakani, T. Akai, K. Akihisa, C. Jiang and J. M. J. S. R. Wood (2020). "Core versus cuttings samples for geochemical and petrophysical analysis of unconventional reservoir rocks." 10(1): 7920.
- Saxena, A., J. Prakash Gupta, J. K. Tiwary, A. Kumar, S. Sharma, G. Pandey, S. Biswas and K. J. S. Raghav Chaturvedi (2024). "Innovative pathways in carbon capture: Advancements and strategic approaches for effective carbon capture, utilization, and storage." 16(22): 10132.
- Shi, S., Z. Wang, D. Qi, W. Guo, Y. J. E. S. Wang, Part A: Recovery, Utilization, and E. Effects (2024). "Investigation of Churn and Annular Flow Transition Boundaries in Vertical Upward Gas-Water Two-Phase Flow." 46(1): 1-21.
- Sircar, A., K. Yadav, K. Rayavarapu, N. Bist and H. J. P. R. Oza (2021). "Application of machine learning and artificial intelligence in oil and gas industry." 6(4): 379-391.
- Sun, N., T. Ye and R. J. P. o. F. Wang (2024). "Direct simulations of bedrock core and cuttings transport phenomena in reverse circulation drilling." 36(12).
- Swasdisevi, T., W. Thianngoen and S. J. F. Prachayawarakorn (2024). "Mathematical Modeling and Design of Parboiled Paddy-Impinging Stream Dryer Using the CFD-DEM Model." 13(10): 1559.
- Tee, J. Z., K. H. Tan, I. L. H. Lim, K. Zhou and O. J. I. P. I. S. G. T. E. Anaya-Lara (2019). "Integration of Offshore Wind with O&G Platforms with an Energy Storage System." 1-5.
- van Deurzen, L. H. (2024). Ultrawide Bandgap Nitride Photonics on Bulk Substrates, Cornell University.
- Wang, F. Z., I. Animasaun, T. Muhammad, S. J. A. J. f. S. Okoya and Engineering (2024). "Recent advancements in fluid dynamics: drag reduction, lift generation, computational fluid dynamics, turbulence modelling, and multiphase flow." 49(8): 10237-10249.
- Wang, H., Y. Ge and L. J. N. G. I. B. Shi (2017). "Technologies in deep and ultra-deep well drilling: Present status, challenges and future trend in the 13th Five-Year Plan period (2016-2020)." 4(5): 319-326.
- Wang, X. J. M. I. T. (2017). "Application of artificial intelligence in oil and gas industry." 3(1): 117-119.
- Wijayanta, S., I. Catrawedarma, A. J. F. M. Hudaya and Instrumentation (2022). "Statistical characterization of the interfacial behavior of the sub-regimes in gas-liquid stratified two-phase flow in a horizontal pipe." 83: 102107.
- Xu, Z., X. Song, Y. Sun, M. Zhou and G. J. I. J. o. F. E. Li (2025). "Comprehensive review of cuttings transport in wellbore drilling: Mechanisms, challenges, and future directions." 2(3).
- Yang, S., H. Wang and Y. J. M. Wang (2024). "Temperature-sensitive materials for oil and gas drilling applications." 29(7): 1471.
- Yaqub, M. W. and R. J. D. C. E. Pendyala (2024). "Flow regime transition maps and pressure loss prediction of gas, oil and water three-phase flow in the vertical riser downstream 90° bend using data driven approach." 12: 100174.
- Zhu, J., Z. Huang, Y. Ma, D. Xie, X. Yang and C. J. S. p. Zhou (2020). "Hydraulic structure design and downhole flow field optimization of geophysical drill bits in a limestone stratum." 103(3): 0036850420931257.
- Zhu, X., X. Wang, Y. Liu, Y. Luo and H. J. L. Zhang (2023). "Probing the effect of cuttings particle size on the friction and wear mechanism at the casing friction interface: a molecular dynamics study." 39(37): 13386-13398.

پیشرفت در فناوری‌های جریان چندفازی برای انتقال پایدار خرده‌های حفاری در صنعت نفت و گاز

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چکیده

انتقال خرده‌های حفاری یکی از فرآیندهای کلیدی در عملیات حفاری نفت و گاز است که به‌طور مستقیم بر بهره‌وری، ایمنی و انطباق زیست‌محیطی تأثیر می‌گذارد. این مقاله مروری، پیشرفت‌های اخیر در فناوری‌های جریان چندفازی را که دینامیک سیالات محاسباتی، هوش مصنوعی، رباتیک و مواد پایدار را با تمرکز بر کاربردهای عملی در میدان ترکیب می‌کنند، مورد بررسی قرار می‌دهد. تحلیل تطبیقی داده‌های میدانی و شبیه‌سازی‌ها نشان می‌دهد که سیستم‌های پایش لحظه‌ای می‌توانند زمان‌های غیرمولد را بین ۵۲ تا ۰۳ درصد کاهش دهند، در حالی که مدل‌های مبتنی بر دینامیک سیالات محاسباتی، دقت پیش‌بینی را بین ۵۱ تا ۰۲ درصد افزایش می‌دهند و کنترل بهتری بر سرعت چرخشی در حلقه حفاری و تعلیق کاتینگ‌ها در چاه‌های افقی و فشار و دمای بالا فراهم می‌سازند. استفاده از سیالات حفاری زیست‌تخریب‌پذیر و نانوافزوده باعث کاهش ۵۳ تا ۰۴ درصدی اثرات زیست‌محیطی و کاهش هزینه‌های دفع پسماند می‌شود و راهکاری اقتصادی برای پروژه‌های حساس از نظر محیط‌زیست ارائه می‌دهد. همچنین، سیستم‌های رباتیکی حمل و مدیریت خرده‌های حفاری و ایمنی کارکنان را تا ۰۵ درصد افزایش داده و امکان عملیات بدون سرنشین و پیوسته را در محیط‌های دریایی فراهم می‌سازد. با وجود این دستاوردها، چالش‌هایی همچنان در مقیاس‌پذیری مدل‌های پیشرفته به سطح عملیات میدانی و توازن میان هزینه محاسباتی و قابلیت اجرا در محل باقی‌مانده است. این مطالعه پیشنهاد می‌کند که سیستم‌های کنترل مبتنی بر هوش مصنوعی با شبیه‌سازی‌های CFD-DEM ادغام شده و پلتفرم‌های رباتیکی مازولار برای مدیریت خودکار مواد جامد به کار گرفته شوند. با پیوند دادن مدل‌سازی نظری با تجربیات میدانی معتبر، این مقاله یک نقشه راه عملی برای پیاده‌سازی سیستم‌های پایدار، کارآمد و داده‌محور انتقال خرده‌های حفاری در صنعت نفت و گاز ارائه می‌کند.

واژگان کلیدی: انتقال خرده‌های حفاری، جریان چندفازی، دینامیک سیالات محاسباتی، هوش مصنوعی، نانوفناوری، رباتیک، حفاری پایدار