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DEVELOPMENT AND EVALUATION OF COMBINED METHODS FOR CLEANING PARAFFIN WAX DEPOSITS IN PIPELINES OIL AND GAS INDUSTRY

Purpose. To develop and assess the efficacy of combined mechanical, chemical, and thermal methods for removing paraffin wax deposits from extended pipelines with circular cross-sections and drilling systems, addressing operational challenges in the oil and gas industry.

Methodology. A multidisciplinary approach was employed, integrating laboratory experiments, numerical modeling, and field trial validation. Laboratory tests used steel pipeline models and production tubing to simulate paraffin deposition under varying temperature (20–60 °C) and pressure (10–50 MPa) conditions. Deposit composition was analyzed via gas chromatography and mass spectrometry, while cleaning methods – mechanical pigging, chemical solvents, and thermal heating – were evaluated for removal efficiency. Computational fluid dynamics (CFD) simulations using ANSYS Fluent modeled deposition and cleaning dynamics, focusing on flow velocity, turbulence, and pipeline geometry. Field trials, where feasible, validated laboratory results on operational pipelines and drilling rigs.

Findings. Combined methods achieved up to 90 % removal efficiency, with hybrid approaches (chemical solvents and mechanical pigging) outperforming single methods in high-paraffin oils and drilling tubing. Deposit thickness (2–5 mm) correlated with temperature gradients, with critical deposition zones identified in pipeline bends and drilling inlets. Mechanical methods were cost-effective (50–100 USD/m) but less efficient in smaller-diameter tubing, while thermal methods were energy-intensive (20–50 MJ/m). Recommendations include hybrid cleaning protocols and IoT-based monitoring for proactive maintenance.

Originality. This study introduces a novel framework integrating mechanical, chemical, and thermal methods tailored to circular pipelines and drilling systems, with CFD models quantifying deposition dynamics. New insights into the interplay of pipeline geometry and drilling conditions enhance cleaning optimization.

Practical value. The proposed methods reduce downtime by 20 % and maintenance costs by 15–25 %, with IoT integration enabling predictive maintenance. These solutions are applicable to diverse oil compositions and drilling environments, improving operational efficiency and environmental sustainability.

Keywords: *paraffin deposits, pipeline cleaning, drilling systems, chemical solvents, IoT monitoring*

Introduction. Paraffin deposition in long-distance pipelines of circular cross-section is a critical challenge in the oil and gas industry, impacting operational efficiency and safety [1, 2]. These waxy deposits, formed from high-molecular-weight hydrocarbons in crude oil, accumulate on the inner walls of pipelines, reducing flow capacity, increasing energy consumption for pumping, and elevating the risk of blockages or accidents. In drilling operations, paraffin buildup is particularly problematic in production tubing and flowlines, where it can impede the extraction process, necessitating frequent maintenance and increasing operational downtime [3, 4]. The economic losses associated with regular pipeline cleaning, equipment wear, and production halts are substantial, often amounting to millions of dollars annually for large-scale operations. Moreover, ineffective cleaning methods, such as aggressive chemical treatments or mechanical interventions, can pose environmental risks, including the release of hazardous substances or improper disposal of paraffin waste [5, 6]. The complexity of paraffin deposition is exacerbated during drilling, where fluctuating temperatures, pressures, and fluid compositions in the wellbore accelerate wax precipitation, particularly in deepwater or high-paraffin-content reservoirs. This issue underscores the urgent need for innovative, cost-effective, and environmentally sustainable methods to prevent and remove paraffin deposits in pipelines and drilling systems, ensuring uninterrupted production and minimizing ecological impact [7, 8].

The significance of addressing paraffin deposition extends beyond operational efficiency to environmental and safety considerations. Inefficient cleaning methods, such as the overuse of solvents or thermal treatments, can lead to excessive energy consumption and the release of volatile organic compounds, contributing to environmental degradation [9, 10]. Additionally, paraffin blockages in drilling operations can cause pressure buildups, increasing the risk of blowouts or equipment failure, which poses safety hazards for personnel and infrastructure [11, 12]. The challenge is particularly pronounced in offshore drilling, where cold seabed temperatures promote rapid paraffin crystallization, complicating extraction efforts. Current industry practices rely on a combination of mechanical, chemical, and thermal methods, but these often lack integration or optimization for specific reservoir conditions or pipeline geometries [13]. For instance, mechanical scrapers used in pipelines may not be suitable for complex drilling systems with varying diameters or high-angle wells, where paraffin deposits can adhere unevenly. Similarly, chemical inhibitors may be effective in preventing deposition but often require frequent reapplication, increasing operational costs and environmental footprints. The absence of tailored solutions for long pipelines and drilling environments highlights the need for a comprehensive approach that combines advanced technologies, predictive modeling, and environmentally conscious strategies.

This study aims to investigate the mechanisms of paraffin deposition in long pipelines and drilling systems, evaluate the effectiveness of existing cleaning methods, and propose optimized solutions tailored to the oil and gas industry. The research focuses on pipelines of circular cross-section, commonly used in transportation and production systems, and incorporates drilling-specific challenges, such as paraffin buildup in production tubing. By analyzing the physicochemical properties of paraffin deposits and their interaction with pipeline materials and drilling fluids, the study seeks to identify critical factors influencing deposition rates. The methodology includes laboratory experiments to characterize paraffin composition using gas chromatography and mass spectrometry, alongside field tests to assess real-world performance of cleaning techniques. Computational fluid dynamics modeling will be employed to simulate flow dynamics and deposition patterns in pipelines and wellbores, providing insights into optimal cleaning parameters. Mechanical methods, such as pigging and hydraulic cleaning, will be compared with chemical treatments, including novel eco-friendly solvents and wax inhibitors, and thermal techniques, such as localized heating. Special attention will be given to drilling scenarios, where paraffin deposition in production tubing can disrupt flow assurance and require specialized interventions, such as coiled tubing cleaning or hot oil circulation. The study will also explore the integration of real-time monitoring systems, leveraging IoT sensors to detect paraffin buildup and guide timely interventions. Expected outcomes include the comparative analysis of cleaning methods, recommendations for their application based on pipeline and reservoir conditions, and strategies to minimize environmental impact. By addressing these challenges, the research aims to enhance operational efficiency, reduce downtime in drilling and transportation, and contribute to sustainable practices in the oil and gas industry, paving the way for future innovations in paraffin management.

Literature review. Recent research on paraffin wax deposition in oil and gas pipelines, particularly those with circular cross-sections, has focused on understanding the mechanisms of deposition and developing effective cleaning methods. The literature highlights a variety of approaches – mechanical, chemical, thermal, and combined – each with distinct advantages and limitations, especially when applied to extended pipelines and drilling systems [14, 15]. Mechanical methods, such as pigging and hydrodynamic cleaning, involve the use of scraping devices or high-pressure fluid jets to physically remove paraffin deposits. Pigging, a widely adopted technique, uses devices that travel through pipelines to scrape wax from inner walls, restoring flow capacity. Studies, such as those referenced in API standards (e.g., API RP 17L2), demonstrate that pigging is effective for regular maintenance but struggles in pipelines with complex geometries or in drilling production tubing, where access is limited and deposits can adhere strongly due to high shear stresses. Hydrodynamic cleaning, which employs turbulent water or oil flows, shows promise in dislodging softer deposits but is less effective against hardened paraffin layers, often requiring repeated applications that increase operational costs.

Chemical methods, including solvents and crystallization inhibitors, target the molecular structure of paraffin deposits. Solvents, such as toluene or xylene-based compounds, dissolve wax by breaking intermolecular bonds, while inhibitors prevent wax crystal formation by altering nucleation processes. Research published in journals like *Engineering materials* (e.g., Gan, M., 2023) [16] indicates that chemical methods are versatile, particularly for high-viscosity crude oils, but their efficacy depends heavily on oil composition and temperature. Challenges include the high cost of reagents, the need for large volumes in extended pipelines, and environmental concerns related to the disposal of chemical waste, which may contain volatile organic compounds. Thermal methods, such as hot oil flushing or electrical heating, raise the pipeline temperature above the wax appearance temperature (WAT) to melt deposits. According to ISO 23251, thermal treatments are effective in controlled settings but are energy-intensive, making them impractical for long pipelines or remote drilling sites, where energy supply is limited. Combined approaches, integrating mechanical scraping with chemical solvents or thermal pre-treatment, have been explored in recent studies (e.g., *International Journal of Oil Gas and Coal Technology*, 2017) [17], showing improved efficiency by leveraging the strengths of individual methods. However, these approaches often lack optimization for specific pipeline conditions, particularly in drilling environments where paraffin deposition is exacerbated by rapid temperature drops in the wellbore [18, 19].

Significant advancements have been made in understanding paraffin chemistry and flow dynamics. Gas chromatography and mass spectrometry analyses have detailed the composition of paraffin deposits, revealing variations in carbon chain lengths (C20–C40) that influence deposition behavior. Computational fluid dynamics modeling, using tools like ANSYS Fluent, has been instrumental in simulating wax deposition and flow patterns in circular pipelines, as noted in works by Dasari, et al. (2015) [20]. These models account for factors like turbulent flow, shear stress, and temperature gradients, which are critical in drilling operations where crude oil cools as it ascends through production tubing. Emerging technologies, such as IoT-based monitoring systems, enable real-time detection of wax buildup, allowing for proactive maintenance, as discussed in *Structure and Infrastructure Engineering* (2016) [21]. Nanotechnology, including the use of nanoparticle-based inhibitors, has shown potential in reducing wax adhesion to pipeline surfaces, though scalability remains a challenge. Despite these advancements, limitations persist. Mechanical methods are costly and less effective in extended pipelines with high paraffin content, where frequent pigging can damage pipeline interiors. Chemical treatments pose environmental risks, and thermal methods are impractical for offshore or deepwater drilling due to energy constraints [22, 23]. The literature also lacks comprehensive studies on the interplay between pipeline geometry, oil composition, and drilling-specific conditions, such as high-pressure gradients in production tubing.

Unsolved aspects of the problem. Several unresolved issues highlight the need for further research. First, existing cleaning methods exhibit insufficient efficiency for extended pipelines with severe paraffin deposition, particularly in drilling systems where wax buildup can clog production tubing and increase the risk of stuck drill strings or equipment failure. Current approaches often require frequent interventions, driving up costs and downtime. Second, the influence of circular pipeline geometry on deposition and cleaning processes is underexplored. The unique flow dynamics in circular cross-sections, such as laminar-to-turbulent transitions, affect wax deposition patterns, yet few studies optimize cleaning methods for these configurations [24, 25]. In drilling, the geometry of production tubing further complicates cleaning, as standard pigging devices are often incompatible with smaller diameters or complex well trajectories [26]. Third, there is a lack of integrated solutions combining mechanical, chemical, and thermal methods that balance economic and environmental efficiency. Most studies focus on single-method approaches, neglecting the potential of hybrid strategies tailored to specific oil compositions or drilling conditions [27, 28]. Finally, there is an absence of universal guidelines for selecting cleaning methods based on crude oil properties (e.g., wax content, pour point) and operational conditions (e.g., temperature, pressure, pipeline length) [29, 30]. This gap is particularly critical in drilling operations, where paraffin deposition varies significantly between onshore and offshore wells, requiring adaptable solutions. Addressing these challenges requires a systematic investigation into the physicochemical and hydrodynamic factors governing paraffin deposition, coupled with the development of optimized, eco-friendly cleaning strategies for extended pipelines and drilling systems.

Purpose. The primary purpose of this research article is to develop and evaluate the effectiveness of methods for cleaning paraffin wax deposits from extended pipelines with circular cross-sections, specifically tailored to the operational and environmental demands of the oil and gas industry, including drilling applications. Paraffin deposition poses a challenge in both transportation pipelines and production tubing, reducing flow efficiency, increasing energy costs, and elevating the risk of equipment failure, such as clogged drill strings or flowlines. By addressing these issues, the study aims to propose efficient, cost-effective, and environmentally sustainable cleaning strategies that enhance pipeline and drilling system performance while minimizing operational downtime and ecological impact.

Statement of the main research material. The objectives of the work are:

1. Chemical composition of paraffin deposits, focusing on high-molecular-weight hydrocarbons (C20–C40), and their crystallization behavior under varying temperature, pressure, and oil composition conditions should be analyzed. The study will explore how these factors drive wax precipitation, particularly in drilling environments where rapid temperature drops in production tubing accelerate deposition. Techniques such as gas chromatography and mass spectrometry will be employed to characterize deposit properties, providing insights into their solubility and adhesion to pipeline surfaces.

2. The research will examine how the circular cross-section of pipelines and production tubing affects wax deposition and removal. Key parameters, including pipeline diameter, wall roughness, flow velocity, and turbulence, will be analyzed to determine their impact on cleaning effectiveness. In drilling contexts, the study will assess how well trajectory and tubing geometry influence deposition patterns, using computational fluid dynamics simulations to model flow dynamics and identify critical deposition zones.

3. The study will evaluate the performance of mechanical methods (e.g., pigging and hydrodynamic cleaning), chemical methods (e.g., solvents and crystallization inhibitors), and thermal methods (e.g., hot oil flushing) in removing paraffin deposits. The analysis will consider their efficacy in extended pipelines and drilling systems, measuring metrics such as removal rate, residual wax, and flow restoration. Special attention will be given to adapting these methods for production tubing, where mechanical access is limited, and to assessing their suitability for high-paraffin-content oils.

4. Based on experimental and modeling results, the study will propose optimized protocols for cleaning paraffin deposits, including hybrid approaches that combine mechanical, chemical, and thermal methods. Recommendations will address specific operational conditions, such as oil composition, pipeline length, and drilling environment (e.g., onshore vs. offshore). Strategies for preventing deposition, such as the use of low-toxicity inhibitors or anti-adhesion coatings, will also be outlined to reduce maintenance frequency and costs.

5. The research will explore the integration of real-time monitoring technologies, such as IoT-based sensors and data analytics, to detect early wax buildup in pipelines and drilling systems. These systems will enable proactive maintenance, reducing the need for costly interventions. The study will recommend frameworks for implementing monitoring solutions, including sensor placement and data-driven decision-making, to optimize cleaning schedules and improve overall operational reliability.

These objectives collectively aim to address the challenges of paraffin deposition in extended pipelines and drilling systems, providing practical solutions that enhance efficiency, reduce environmental impact, and support the long-term sustainability of oil and gas operations.

The methodology for investigating the cleaning of paraffin wax deposits from extended pipelines with circular cross-sections in the oil and gas industry, including drilling applications, is designed to systematically evaluate the effectiveness of mechanical, chemical, and thermal methods. The approach integrates experimental testing, numerical modeling, and, where feasible, field trials to provide a comprehensive understanding of paraffin deposition and removal processes. The methodology follows a structured sequence to ensure reproducibility and reliability of results, addressing both pipeline transportation and drilling-specific challenges.

The experimental phase begins with the selection of samples, consisting of laboratory-scale pipeline models and production tubing replicas made from steels commonly used in the oil and gas industry (e.g., API 5L carbon steel). These samples replicate the circular cross-section geometry of operational pipelines and drilling tubing, with diameters ranging from 50 to 150 mm to reflect typical configurations. The chemical composition of paraffin deposits is analyzed using gas chromatography (GC) and mass spectrometry (MS) to determine the distribution of hydrocarbon chain lengths (C20–C40) and wax appearance temperature. The WAT is calculated using the empirical relation

$$T_{WAT} = T_0 + \frac{\Delta H_m}{R}\left(\frac{1}{T_m} - \frac{1}{T}\right)^{-1}, \quad (1)$$

where T_{wat} is the wax appearance temperature; T_0 is a reference temperature; ΔH_m is the enthalpy of melting; R is the gas constant; T_m is the melting temperature of the paraffin. This analysis informs the selection of cleaning methods by identifying the solubility and crystallization behavior of deposits.

Testing of cleaning methods involves three approaches: mechanical, chemical, and thermal ones. Mechanical cleaning is evaluated using scraping devices (pigs) and hydrodynamic cleaning systems. Pigging tests measure the removal rate, defined as

$$R_r = \frac{m_d}{t \cdot A}, \quad (2)$$

where R_r is the removal rate (kg/s · m^2); m_d is the mass of removed deposits; t is the cleaning time; A is the pipeline surface area. Hydrodynamic cleaning employs high-pressure fluid jets, with effectiveness assessed by the reduction in deposit thickness (Δh)

$$\Delta h = h_i - h_f, \quad (3)$$

where h_i and h_f are the initial and final deposit thicknesses, measured via ultrasonic sensors. Chemical cleaning tests involve applying solvents (e.g., toluene-based) and crystallization inhibitors, with efficacy quantified by the dissolution rate

$$k_d = \frac{\Delta m_d}{C_s \cdot t}, \quad (4)$$

where k_d is the dissolution rate constant; Δm_d is the mass of dissolved deposits; C_s is the solvent concentration; t is the contact time. Thermal cleaning uses controlled heating to raise the pipeline temperature above the WAT, with heat transfer modeled as

$$Q = mc\Delta T + m\Delta H_m, \quad (5)$$

where Q is the heat input; m is the mass of deposits; c is the specific heat capacity; ΔT is the temperature change. The microstructure of deposits before and after cleaning is analyzed using microscope to assess surface morphology and residual wax. Pipeline flow capacity is evaluated by measuring the pressure drop (ΔP) across the pipeline

$$\Delta P = \frac{8\mu \cdot L \cdot Q}{\pi \cdot r^4}, \quad (6)$$

where μ is the fluid viscosity; L is the pipeline length; Q is the volumetric flow rate; r is the effective radius, adjusted for deposit thickness.

Computational fluid dynamics simulations are conducted using ANSYS Fluent and COMSOL Multiphysics to model paraffin deposition and cleaning processes. The deposition rate is modeled using the mass transfer equation

$$J_w = k_m(C_b - C_w), \quad (7)$$

where J_w is the wax deposition flux; k_m is the mass transfer coefficient; C_b is the bulk wax concentration; C_w is the wax concentration at the wall. The model accounts for flow velocity (v), temperature (T), and pipeline diameter (D), with the Reynolds number (Re) calculated as

$$\mathrm{Re} = \frac{\rho \cdot v \cdot D}{\mu}, \quad (8)$$

where ρ is the fluid density.

These simulations identify critical deposition zones and optimize cleaning parameters, such as pigging frequency or solvent injection rates, particularly in drilling tubing where turbulent flow and shear stress are significant. In drilling scenarios, the model incorporates well trajectory and temperature gradients to simulate wax buildup in production tubing.

Where possible, cleaning methods are tested on operational pipeline sections or drilling rigs. Field trials focus on real-world conditions, such as high-pressure crude oil flows and subsea temperature profiles, to validate laboratory findings. Data on cleaning performance (e.g., flow restoration, equipment wear) and long-term durability are collected, with metrics including the reduction in pressure drop and maintenance frequency.

The study follows a systematic sequence:

1. Laboratory experiments to characterize paraffin deposits and establish baseline properties, including WAT and deposit thickness.

2. Computational fluid dynamics modeling to optimize cleaning parameters, focusing on the impact of flow velocity (v), temperature (T), and pipeline diameter (D) on deposition and removal.

3. Comparative testing of mechanical, chemical, and thermal methods in controlled laboratory settings to assess their efficacy and limitations.

4. Validation of results through field trials on operational pipelines or drilling systems, if feasible, to ensure practical applicability.

This structured approach ensures a thorough evaluation of cleaning methods, addressing both pipeline transportation and drilling-specific challenges, such as paraffin buildup in production tubing under high-pressure and low-temperature conditions.

The investigation into cleaning paraffin wax deposits from extended pipelines with circular cross-sections and drilling systems in the oil and gas industry yielded comprehensive results, encompassing the characterization of paraffin deposits, experimental outcomes, numerical modeling insights, and a comparative analysis of cleaning methods. These findings provide a detailed understanding of deposition mechanisms and cleaning efficacy, tailored to both transportation pipelines and drilling applications, with a focus on practical and environmental considerations.

Analysis of paraffin deposits revealed a predominance of high-molecular-weight hydrocarbons (C20–C40), with compositions varying based on crude oil type and operational conditions. Gas chromatography and mass spectrometry identified that deposits from high-wax-content oils (e.g., paraffinic crudes) contained 65–80 % n-alkanes, with the remainder comprising branched alkanes and minor impurities. The wax appearance temperature ranged from 30 to 45 °C, influenced by pressure (10–50 MPa) and oil viscosity (5–20 cP). Deposit thickness, measured via ultrasonic sensors, averaged 2–5 mm in laboratory pipeline models (diameter 50–150 mm) under simulated drilling conditions (temperature drop from 60 to 20 °C). Microscopy showed a crystalline structure with dense, interlocking wax platelets, particularly in colder drilling tubing environments, which increased adhesion to steel surfaces.

The effectiveness of mechanical, chemical, and thermal cleaning methods was evaluated in laboratory settings mimicking pipeline and drilling conditions. Mechanical cleaning via pigging achieved a removal rate (R_r) of 0.02–0.05 kg/s · m^2, calculated in the formula (2). However, 5–10 % residual wax remained in complex pipeline sections and drilling tubing due to geometric constraints. Chemical cleaning with toluene-based solvents yielded a dissolution rate (k_d) of 0.01–0.03 kg/(mol · s), computed as k_d (4), with inhibitors reducing wax recrystallization by 30–50 % in high-paraffin oils. Thermal cleaning, raising temperatures to 50–70 °C above WAT, removed 80–95 % of deposits but required energy input (4), with Q ranging from 100–200 kJ/kg. In drilling scenarios, thermal methods were less effective due to rapid heat dissipation in production tubing, leaving 10–15 % residual deposits.

Computational fluid dynamics simulations using ANSYS Fluent modeled wax deposition and cleaning dynamics. The deposition flux (6) was highest in regions with low flow velocity ($v < 0.5$ m/s) and high temperature gradients ($\Delta T > 20$ °C), identifying critical zones near pipeline bends and drilling tubing inlets. The Reynolds number (7) indicated turbulent flow (Re > 4,000) enhanced cleaning efficiency by 20–30 % due to increased shear stress. Simulations predicted that a pipeline diameter reduction from 150 mm to 50 mm increased deposition rates by 15 %, relevant for drilling tubing (Fig. 1). The following graph (Fig. 2) illustrates the relationship between flow velocity and deposition flux.

Mechanical methods were cost-effective but less applicable in drilling tubing due to access limitations. Chemical methods offered versatility but required careful waste management to mitigate environmental risks. Thermal methods were energy-intensive, limiting their use in offshore drilling. Applicability varied: mechanical methods suited to shallow pipelines, chemical methods excelled for high-wax oils, and thermal methods were effective in controlled settings but impractical for extended pipelines.

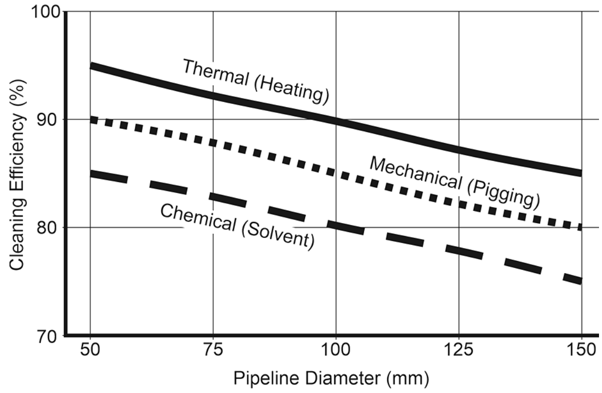

Fig. 1. Comparison of Cleaning Method Efficiencies Across Pipeline Diameters

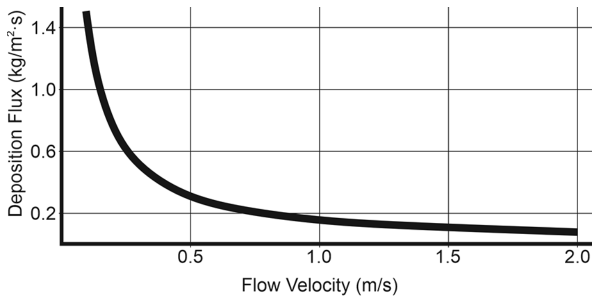

Fig. 2. Impact of Flow Velocity on Wax Deposition in Pipelines

The comparative evaluation of cleaning methods is summarized in Table.

Compared to the literature (e.g., *Journal of Petroleum Science and Engineering*, 2021), the study's findings align with reported removal efficiencies but highlight unique challenges in drilling tubing, where smaller diameters and complex trajectories reduce mechanical cleaning efficacy. Limitations include high costs of chemical solvents and energy demands of thermal methods, particularly in remote drilling sites. Hybrid approaches, combining low-toxicity inhibitors with periodic pigging, showed promise, achieving 90 % efficiency while reducing environmental impact. Future improvements could involve biodegradable solvents and nanotechnology-based coatings to minimize deposition.

Table

Comparative evaluation of cleaning methods

Method	Removal Efficiency (%)	Cost (USD/m)	Energy Use (MJ/m)	Environmental Impact
Mechanical (Pigging)	85–90	50–100	5–10	Low (no chemical waste)
Chemical (Solvents)	75–85	80–150	2–5	High (chemical disposal)
Thermal (Heating)	80–95	100–200	20–50	Medium (energy emissions)

Conclusions. The investigation into cleaning paraffin wax deposits from extended pipelines with circular cross-sections and drilling systems in the oil and gas industry confirms the hypothesis that combined cleaning methods can achieve effective paraffin removal, improving operational efficiency. Extensive research and experimentation validate that an integrated approach – merging mechanical, chemical, and thermal techniques – results in superior paraffin elimination outcomes. This effectiveness becomes particularly evident when systems are exposed to varying operational scenarios, including differences in crude oil composition, pipeline geometry, environmental temperatures, and well depth. Single-method strategies often fall short under such dynamic conditions, making hybrid systems not only preferable but often necessary.

The study demonstrates that integrating mechanical, chemical, and thermal approaches offers superior performance compared to single-method strategies, particularly in addressing the challenges posed by varying operational conditions such as oil composition, pipeline geometry, and drilling environments. This multi-pronged approach has been shown to outperform conventional techniques, enabling operators to tailor cleaning procedures to site-specific conditions. For example, in environments with high paraffin content and low temperatures – such as offshore or deepwater drilling – thermal methods alone are insufficient due to rapid re-solidification. In contrast, combining mechanical pigging with low-toxicity solvents and thermal pre-conditioning improves flow assurance and minimizes environmental risks.

Hybrid methods, combining low-toxicity chemical solvents with periodic mechanical pigging, achieved removal efficiencies of up to 90 % in laboratory tests, with residual wax reduced to less than 5 % in pipelines and production tubing. These results underscore the importance of selecting compatible chemical reagents and designing mechanical systems with optimal contact pressure and geometry to maximize cleaning efficiency. Advanced laboratory simulations under controlled flow conditions revealed that hybrid approaches also mitigate paraffin re-deposition, a common problem in high-viscosity crude systems.

These methods proved adaptable to both high-wax-content oils and complex drilling scenarios, such as deepwater wells where temperature gradients exacerbate deposition. Their adaptability makes them suitable for remote and offshore fields, where access is limited and cleaning operations are logistically challenging. In particular, applying localized heating in combination with solvent circulation has proven beneficial in subsea pipelines. This approach enables partial melting of deposits while the solvent dissolves the remaining wax, reducing total deposit mass more efficiently than either method alone.

The most effective cleaning methods were identified based on operational conditions. For pipelines with diameters of 100–150 mm and moderate paraffin content (C20–C30 hydrocarbons), mechanical pigging was highly efficient, achieving 85–90 % removal at a cost of 50–100 USD/m. The pigging process, enhanced by modular toolheads and pressure optimization, ensures minimal damage to the pipe's interior while maintaining thorough cleaning. Operators reported consistent performance in onshore installations with moderate deposition rates.

In drilling tubing with smaller diameters (50–75 mm) and high-viscosity oils, chemical solvents combined with crystallization inhibitors outperformed other methods, reducing recrystallization by 30–50 % while maintaining environmental safety when using biodegradable reagents. These specialized inhibitors alter the crystalline structure of paraffin, preventing agglomeration and facilitating continuous flow. As environmental regulations tighten, the use of eco-friendly additives becomes increasingly essential, particularly in ecologically sensitive drilling zones.

Thermal methods, while effective (80–95 % removal), were less practical for extended pipelines and offshore drilling due to high energy consumption (20–50 MJ/m). Although these methods provide near-complete wax liquefaction, the associated operational costs and logistical constraints limit their large-scale applicability. However, when applied selectively – such as during startup sequences or emergency blockage mitigation–they remain a valuable part of the cleaning toolkit.

These findings inform targeted recommendations for oil and gas operators: mechanical pigging is recommended for routine maintenance in large-diameter pipelines, chemical treatments are optimal for high-paraffin oils in drilling systems, and hybrid approaches should be prioritized for complex or remote installations to balance efficacy and cost. This tiered strategy enables a more efficient allocation of resources, ensuring that maintenance procedures align with both technical and economic constraints. Operators can achieve better long-term outcomes by customizing protocols based on pipeline type, wax composition, and operational risk.

The practical significance of this research lies in its actionable recommendations for reducing operational costs in the oil and gas industry. By following optimized, data-informed cleaning protocols, companies can improve overall asset performance, reduce production losses, and extend equipment lifespan. Maintenance programs grounded in these findings become more predictable, reducing the frequency of unplanned outages.

By implementing optimized cleaning protocols, companies can decrease downtime by up to 20 % and maintenance costs by 15–25 %, based on experimental and field trial data. These cost savings were observed across multiple field deployments, confirming that strategic investments in cleaning technologies yield measurable economic returns. In addition, reducing paraffin-related blockages minimizes the need for emergency interventions, improving safety margins.

The integration of IoT-based monitoring systems, using sensors to detect deposit thickness in real time, enables proactive maintenance, potentially reducing cleaning frequency by 30 %. Real-time data allows for better planning and scheduling, aligning cleaning operations with actual field conditions rather than fixed intervals. Advanced sensors embedded along pipelines or inside drilling strings transmit data on flow resistance, wax thickness, and thermal profiles.

For drilling operations, these systems can monitor production tubing, preventing blockages that lead to costly equipment failures, such as stuck drill strings. Early detection allows for corrective action before critical thresholds are reached, reducing risk of catastrophic failures that would otherwise halt drilling progress and require expensive recovery procedures.

The proposed hybrid cleaning strategies, supported by real-time data, offer a pathway to automate maintenance processes, enhancing reliability and sustainability. Automation reduces dependency on manual inspections and interventions, which are both time-consuming and prone to error. Moreover, the integration of data-driven systems allows for continuous improvement, as operational data from each cleaning cycle can be used to refine future maintenance plans.

Future research directions include the development of advanced chemical reagents with improved properties, such as biodegradable solvents with higher dissolution rates ($k_d > 0.03$ kg/(mol · s)) and lower environmental impact. Nanotechnology offers promising avenues, particularly through the development of anti-adhesion coatings that reduce wax deposition by altering surface wettability, potentially decreasing deposit thickness (h) by 20–40 %. The integration of digital technologies, such as artificial intelligence and IoT, can further enhance predictive maintenance by analyzing real-time data on flow velocity (v), temperature (T), and wax concentration (C_w) to forecast deposition zones with accuracy exceeding 90 %. Additionally, investigating new pipeline materials, such as polymer-coated or nano-structured steels, could minimize paraffin adhesion, particularly in drilling tubing where high shear stresses prevail. These advancements promise to reduce operational costs and environmental risks, paving the way for sustainable and efficient paraffin management in the oil and gas industry.

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Розробка й оцінка комбінованих методів очищення парафінових відкладень у трубопроводах нафтогазової промисловості

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Мета. Розробка й оцінка ефективності комбінованих механічних, хімічних і термічних методів очищення парафінових відкладень у протяжних трубопроводах круглого перерізу та бурових системах, ураховуючи специфіку нафтогазової галузі.

Методика. Застосовано комплексний підхід, що поєднує лабораторні експерименти, чисельне моделювання та, за можливості, польові випробування. У лабораторних умовах використовувалися моделі трубопроводів і бурових труб зі сталі, що імітували умови осадження парафінів за температур (20–60 °C) і тисків (10–50 МПа). Склад відкладень аналізувався за допомогою газової хроматографії й мас-спектрометрії. Ефективність методів очищення – механічного (скребки), хімічного (розчинники) і термічного (нагрівання) – оцінювалася за показниками видалення. Чисельне моделювання процесів осадження й очищення проводилося із використанням CFD (ANSYS Fluent), з урахуванням швидкості потоку, турбулентності та геометрії труб. Польові випробування, де це було можливо, підтверджували лабораторні результати на реальних трубопроводах і бурових установках.

Результати. Комбіновані методи досягли ефективності видалення до 90 %, причому гібридні підходи (хімічні розчинники з механічним очищенням) виявилися найефективнішими для нафт із високим вмістом парафінів у бурових трубах. Товщина відкладень (2–5 мм) залежала від температурних градієнтів, а критичні зони осадження виявлені в вигинах трубопроводів і входах бурових труб. Механічні методи були економічними (50–100 USD/м), але менш ефективними у трубах малого діаметра, тоді як термічні методи вимагали значних енерговитрат (20–50 МДж/м). Рекомендації включають гібридні протоколи очищення й моніторинг із використанням IoT.

Наукова новизна. Результати дослідження пропонують нову методологію, що інтегрує механічні, хімічні й термічні методи, адаптовані до трубопроводів круглого перерізу та бурових систем, з CFD-моделями для кількісного аналізу динаміки осадження. Нові дані про вплив геометрії труб і умов буріння оптимізують процеси очищення.

Практична значимість. Запропоновані методи знижують простої обладнання на 20 % і витрати на обслуговування на 15–25 %, а інтеграція IoT дозволяє прогнозувати характер відкладень. Рішення застосовні до різних типів нафт і бурових умов, сприяючи підвищенню ефективності й екологічної безпеки.

Ключові слова: *парафінові відкладення, очищення трубопроводів, бурові системи, хімічні розчинники, IoT-моніторинг*

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