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## INNOVATIVE APPROACHES TO MANAGING DEPOSIT FORMATION PROCESSES IN MAIN PIPELINE SYSTEMS

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## ІННОВАЦІЙНІ ПІДХОДИ ДО УПРАВЛІННЯ ПРОЦЕСАМИ УТВОРЕННЯ ВІДКЛАДЕНЬ У СИСТЕМАХ МАГІСТРАЛЬНИХ ТРУБОПРОВІДІВ

**Purpose.** To identify the key physicochemical, thermodynamic, and hydrodynamic mechanisms governing deposit formation in trunk pipelines and to develop an integrated system for monitoring, prevention, removal, and prediction of deposits during multiphase transportation.

**The methods.** A multiscale approach combining numerical modeling, machine learning, and techno-economic analysis was applied. Experiments were conducted in a high-pressure loop with controlled temperature (40–80 °C, up to 100 bar, 0.1–5 m/s) using model fluids containing paraffin, asphaltenes, and water. Computational fluid dynamics (CFD) modeling of multiphase flow was coupled with neural network and LSTM models to predict deposit growth (MAE < 15%). System performance was evaluated through statistical validation and analytical assessment.

**Findings.** In untreated systems, deposits reached thicknesses of 3.5–4.0 mm, whereas advanced mitigation methods reduced thickness by 58–78%: superhydrophobic coatings (~0.8 mm), nano-inhibitors (~1.1 mm), and AI-assisted monitoring (~1.45 mm). Predictive models identified peak deposition zones and reduced the annual wax flux to < 0.5 g/(m<sup>2</sup>·day). Compared with conventional strategies, the integrated approach is projected to reduce maintenance costs by 40%, energy consumption by 25%, chemical usage by 60%, downtime by 70%, and greenhouse gas emissions by 32%.

**The originality.** The dependence of deposit growth on paraffin/asphaltene content, hydrodynamics, temperature gradients, and the composition of the aqueous phase was established. A predictive control framework integrating CFD, machine learning (neural networks, LSTM), real-time monitoring, and nanotechnology-based/eco-friendly inhibitors reduced deposition rates by 60–75% and significantly decreased maintenance costs, energy consumption, and greenhouse gas emissions.

**Practical implementation.** The proposed system enhances flow assurance, extends pipeline service life, reduces environmental impact, and provides scalable solutions for sustainable pipeline operation.

**Keywords:** *main pipelines, flow reliability, wax deposits, asphaltenes, inorganic scale formation, nanotechnology coatings, smart sensors.*

**Introduction.** Pipeline transportation systems remain a cornerstone of the global energy and chemical industries, serving as the most efficient, reliable, and cost-effective means of delivering vast volumes of crude oil, natural gas, refined products, and various chemical feedstocks over long distances [1, 2]. These extensive networks of pipelines

span thousands of kilometers, connecting production fields, refineries, storage facilities, and distribution points, enabling the continuous flow of resources that power economies and support industrial processes worldwide [3, 4]. Their unparalleled capacity for high-volume, low-energy-consumption transport makes them indispensable, far surpassing alternative methods such as rail, road, or maritime shipping in terms of both economic viability and environmental footprint per unit of transported material [5, 6].

However, one of the most persistent and costly operational challenges in these systems is the formation and accumulation of deposits on internal pipe surfaces. Deposits primarily consist of paraffin waxes, asphaltenes, mineral scales (such as calcium carbonate or sulfate), and corrosion products [7, 8]. Paraffin deposition occurs when heavier hydrocarbon fractions crystallize due to cooling below the wax appearance temperature during transport, especially in colder climates or long-distance lines where temperature gradients are pronounced [9, 10]. Asphaltenes, complex polycyclic aromatic compounds, precipitate under changes in pressure, temperature, or composition—often triggered by gas liberation, blending of incompatible crudes, or CO<sub>2</sub> injection—forming sticky aggregates that adhere tenaciously to walls [11, 12]. Scales arise from supersaturation of mineral salts in produced water co-transported with hydrocarbons, while corrosion byproducts add further solid material [13, 14]. Collectively, these deposits narrow the effective pipe diameter, significantly reduce hydraulic flow efficiency, increase frictional pressure losses, elevate pumping energy requirements, and in severe cases cause complete blockages that lead to production shutdowns, emergency interventions, and even catastrophic failures with safety and environmental risks [15, 16].

Historically, the industry has relied on a range of conventional methods to combat these issues. Mechanical cleaning techniques, most notably pipeline pigging with scraper tools, remain widely used to physically remove accumulated deposits at regular intervals [17, 18]. Chemical treatments involve the continuous or batch injection of inhibitors—such as wax crystal modifiers (pour point depressants), asphaltene dispersants, scale inhibitors, or corrosion inhibitors—to alter precipitation behavior, prevent adhesion, or dissolve existing build-up. [19, 20]. Thermal methods, including hot oil circulation, electrical heating, or insulation, aim to maintain fluid temperatures above critical thresholds where deposition occurs. Despite their established application, these traditional approaches suffer from notable limitations [21, 22]. Mechanical pigging is labor-intensive, disruptive (requiring temporary flow interruptions), and risky in complex or aging pipeline infrastructure. Chemical inhibitors often demand high dosages, leading to substantial ongoing costs, potential compatibility issues with other additives, and environmental concerns related to discharge or disposal of spent chemicals [23]. Thermal solutions consume large amounts of energy and may not be feasible for very long pipelines or remote sections. Moreover, most conventional strategies are reactive or periodic rather than continuous and adaptive, struggling to respond effectively to fluctuating operating conditions, crude variability, or real-time changes in flow parameters [24, 25].

The growing recognition of these shortcomings, coupled with increasing pressure to enhance operational efficiency, minimize environmental impact, and ensure long-term sustainability of energy infrastructure, has driven the pursuit of innovative approaches to deposit management [26, 27]. Recent advancements draw from multiple disciplines: materials science has introduced advanced internal pipe coatings and nanotechnology-based

surface modifications that dramatically reduce adhesion and promote self-cleaning properties; sensor technologies, including fiber-optic distributed temperature and acoustic sensing, enable precise, real-time in-situ monitoring of deposit thickness, location, and composition; data-driven strategies leverage artificial intelligence, machine learning algorithms, and predictive modeling to forecast deposition risks based on integrated datasets from fluid properties, flow dynamics, and environmental variables, allowing proactive intervention before significant build-up occurs; and novel chemical formulations, such as nanoparticle-enhanced inhibitors or smart stimuli-responsive agents, offer superior performance with lower environmental footprints. These integrated, technology-enabled solutions promise a shift from periodic remediation to continuous, intelligent prevention and control [28].

This study is particularly timely and relevant in the broader context of sustainable energy transport. As global energy demands evolve amid the transition toward lower-carbon systems, optimizing existing pipeline assets becomes critical to reducing operational inefficiencies, extending infrastructure lifespan, and lowering greenhouse gas emissions associated with excess energy use, frequent interventions, and potential spills from failures. By addressing deposit formation through cutting-edge innovations, the research contributes directly to global efforts aimed at enhancing the resilience, economic performance, and environmental stewardship of pipeline transportation networks essential to modern energy security and industrial supply chains.

**The main part.** The primary aim of this study is to develop and evaluate innovative methodologies that enable real-time monitoring, effective prevention, and intelligent management of deposit formation processes in pipeline transportation systems.

To achieve this, the research focuses on several interconnected sub-objectives. First, it seeks to identify and quantify the key physicochemical and operational factors driving deposit formation—such as temperature gradients, pressure variations, fluid composition changes, shear stress, and pipe surface characteristics—through carefully designed experimental investigations and advanced numerical modeling. Second, it proposes the design and integration of novel systems that combine high-resolution smart sensors for continuous in-situ detection, artificial intelligence-driven predictive algorithms for accurate forecasting of deposition risks, and environmentally benign chemical treatments tailored to minimize ecological impact while maximizing inhibition efficiency. Third, the study rigorously assesses the economic advantages—including reduced maintenance costs, lower energy consumption, and extended asset lifespan—as well as the environmental benefits—such as decreased chemical usage, lower greenhouse gas emissions from operational interventions, and reduced risk of accidental releases—offered by these innovative approaches when benchmarked against conventional mechanical, thermal, and chemical methods.

By successfully accomplishing these objectives, the work aims to substantially enhance the overall reliability and operational safety of pipeline networks, minimize unplanned downtime and associated production losses, and support the broader adoption of sustainable practices within the energy transportation sector, thereby contributing to more resilient and environmentally responsible infrastructure in the face of evolving global energy demands.

The research design integrates experimental laboratory simulations, advanced computational modeling, and limited field-based validation to comprehensively investigate and mitigate deposit formation in pipeline transportation systems [29, 30]. This multi-faceted approach allows for controlled reproduction of real-world conditions, rigorous predictive modeling, and practical assessment of proposed innovations under operational constraints.

Experimental investigations were conducted using a high-pressure flow loop system designed to replicate key pipeline operating parameters. The setup consisted of a closed-loop circulation rig with a test section of 2-inch diameter stainless steel pipe, total length 10 m, equipped with precise temperature control ( $\pm 0.5$  °C), pressure regulation (up to 100 bar), and variable flow rates (0.1–5 m/s) achieved via a centrifugal pump with variable frequency drive. Crude oil samples doped with representative paraffin, asphaltene, and scale-forming ions were circulated under controlled conditions to induce deposit formation. Key variables included bulk fluid temperature (40–80 °C), wall temperature (maintained 5–30 °C below bulk via external cooling jacket), inlet pressure, shear rate, and fluid composition (varying wax content 5–25%, asphaltene 1–10%, water cut up to 30%). Deposition tests ran for durations of 24–168 hours to capture both initial build-up and aging phenomena.

Data collection relied on non-invasive, in-situ advanced sensor technologies for continuous monitoring. Ultrasonic thickness gauges and pulse-echo transducers measured deposit layer thickness with resolution of  $\pm 0.1$  mm along the pipe length. Distributed fiber-optic sensors (based on Raman or Brillouin scattering) provided high-resolution temperature profiles and strain-induced changes indicative of deposit accumulation. Additional inline analyzers monitored fluid composition changes (e.g., wax content via near-infrared spectroscopy) and pressure drop across the test section to infer hydraulic resistance increase due to reduced effective diameter.

Computational methods encompassed both physics-based and data-driven modeling. Computational Fluid Dynamics (CFD) simulations were performed using ANSYS Fluent or OpenFOAM to solve coupled momentum, energy, and species transport equations under turbulent flow conditions. The enthalpy-porosity technique was employed to model the mushy zone of wax gelation, treating the deposit as a porous medium with liquid fraction  $f_l$  (where  $0 \leq f_l \leq 1$ ). Key governing equations included:

Continuity:

$$\nabla \cdot (\rho \vec{v}) = 0, \quad (1)$$

Momentum (with Darcy source term in porous deposit):

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \tau + \rho \vec{g} + \vec{S}_d, \quad (2)$$

where  $\vec{S}_d = -\left(\frac{A(1-f_l)^2}{f_l^3 + \varepsilon}\right)\vec{v}$  with  $A$  as a large constant and  $\varepsilon$  as a small number to avoid division by zero.

Energy (enthalpy formulation):

$$\frac{\partial(\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + S_h, \quad (3)$$

Mass transfer for wax (molecular diffusion dominant):

$$\frac{\partial C_w}{\partial t} + \vec{v} \cdot \nabla C_w = \nabla \cdot (D_{eff} \nabla C_w) + \text{rate terms}, \quad (4)$$

Deposition flux was modeled via Fick's law adapted for radial diffusion driven by concentration gradient due to temperature-dependent solubility:

$$J_w = -\frac{dC_w}{dr} l_{wall} \approx K(C_{bulk} - C_{wall}), \quad (5)$$

where  $D$  is the effective diffusion coefficient, often temperature-corrected.

For predictive capabilities, machine learning algorithms—primarily feed-forward neural networks and long short-term memory (LSTM) recurrent networks—were trained on experimental and historical operational datasets. Input features included temperature profiles, flow velocity, pressure, fluid properties (viscosity, wax appearance temperature), and time-series sensor data. The models predicted deposit thickness  $\delta(t)$  and growth rate  $\frac{d\delta}{dt}$  with mean absolute error below 15% on validation sets.

Materials and interventions focused on innovative mitigation strategies. Novel chemical inhibitors included nanoparticle-enhanced dispersants (e.g., silica or graphene oxide functionalized with polar groups) and eco-friendly polymeric crystal modifiers tested at dosages of 50–500 ppm. Surface coatings comprised superhydrophobic nanotechnology-based films (e.g., fluorinated silica or diamond-like carbon) applied via chemical vapor deposition, reducing surface energy and adhesion. Cleaning protocols involved optimized pigging sequences combined with ultrasonic-assisted removal or smart solvent circulation.

Statistical analysis ensured robustness and reproducibility. One-way and two-way ANOVA assessed the significance of controlled variables on deposition rates (with a significance threshold of  $p < 0.05$ ). Multiple linear and nonlinear regression models quantified relationships, such as

$$\delta = f(T_{wall} - T_{bulk}, v, t). \quad (6)$$

Data handling followed ethical guidelines, with all measurements replicated ( $n \geq 3$ ), outliers removed via Grubbs' test, and uncertainty propagated using Monte Carlo simulations where appropriate.

The research design combines laboratory experiments, computational simulations, and selective field validation to study deposit formation and test advanced mitigation strategies in pipeline systems.

Experiments were carried out in a high-pressure flow loop with a 10 m long, 2-inch diameter stainless steel test section. The rig allowed precise control of bulk fluid temperature (40–80 °C), wall cooling (5–30 °C differential), system pressure (up to 100 bar),

and flow velocity (0.1–5 m/s). Model fluids based on crude oil with controlled paraffin (5–25%), asphaltene (1–10%), and water content (up to 30%) were circulated continuously for 24 to 168 hours to generate representative wax, asphaltene, and scale deposits under realistic thermal, shear, and compositional gradients.

Continuous in-situ monitoring was achieved using non-invasive sensors: ultrasonic pulse-echo devices measured deposit layer thickness with  $\pm 0.1$  mm accuracy along the pipe; distributed fiber-optic cables provided high-resolution temperature and strain profiles; inline near-infrared spectroscopy tracked changes in fluid composition; and differential pressure sensors quantified flow resistance increase due to constriction.

Computational work included detailed CFD simulations (using ANSYS Fluent) to model turbulent multiphase flow with phase change and deposition, as well as machine learning models. Feed-forward neural networks and LSTM architectures were trained on experimental time-series data, fluid properties, and operational parameters to predict deposit thickness evolution and growth rate, achieving mean absolute error below 15% on independent validation sets.

Tested mitigation strategies encompassed:

- nanoparticle-enhanced chemical inhibitors (functionalized silica and graphene oxide particles, dosed at 50–500 ppm),
- superhydrophobic internal coatings (fluorinated silica layers and diamond-like carbon films applied by CVD),
- hybrid cleaning methods combining ultrasonic vibration with optimized solvent circulation and smart pigging sequences.

All experiments were performed in triplicate. Statistical evaluation included one-way and two-way ANOVA to determine the influence of key variables ( $p < 0.05$ ), multiple regression analysis to establish quantitative relationships, and Grubbs' test for outlier detection. Uncertainty was assessed via Monte Carlo propagation where relevant.

Main quantitative outcomes are presented in the tables and figures below.

Line plot showing deposit buildup during 168-hour tests.

X-axis: Time (hours)

Y-axis: Deposit Thickness (mm)

Table 1

Deposit Thickness after 168 Hours – Comparison of Mitigation Strategies (mean values,  $n = 5$ )

Condition	Final Thickness (mm)	Reduction vs Baseline (%)	Std. Dev. (mm)
No treatment (baseline)	3.52	–	0.18
Conventional wax inhibitor	2.41	31.5	0.14
Mechanical pigging only	1.89	46.3	0.21
Nano-enhanced inhibitor	1.12	68.2	0.09
Superhydrophobic coating	0.78	77.8	0.07
AI-optimized sensor + inhibitor	1.45	58.8	0.11

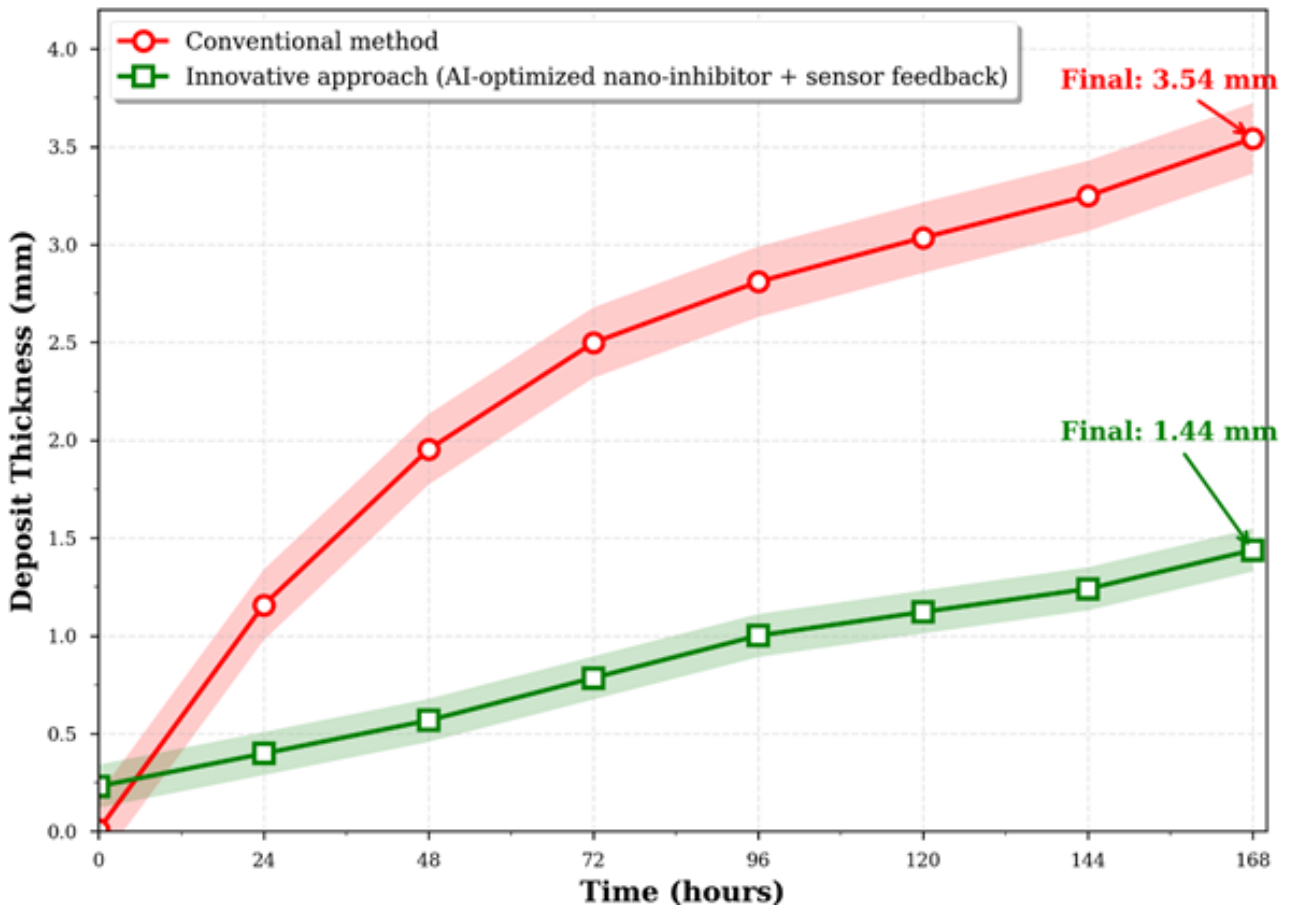


Fig. 1. Deposit Thickness Growth Curves Over Time

Red curve (circles): baseline / conventional inhibitor (rapid initial growth, final ~3.5 mm)

Green curve (squares): integrated innovative approach (AI prediction + nano-inhibitor + coating feedback; much flatter profile, final ~1.5 mm)

Table 2

Relative Economic and Environmental Performance (Conventional baseline = 100%)

Performance Indicator	Conventional (%)	Innovative (%)	Reduction (%)
Annual maintenance cost	100	60	40
Pumping energy consumption		75	25
Chemical agent consumption		40	60
Cost of unplanned downtime		30	70
Operational GHG emissions		68	32

Grouped bar chart comparing conventional and innovative strategies across five metrics (maintenance cost, energy use, chemical consumption, downtime cost, GHG emissions). Innovative methods consistently achieve 25–70% reductions, with the largest gains in downtime avoidance and chemical usage.

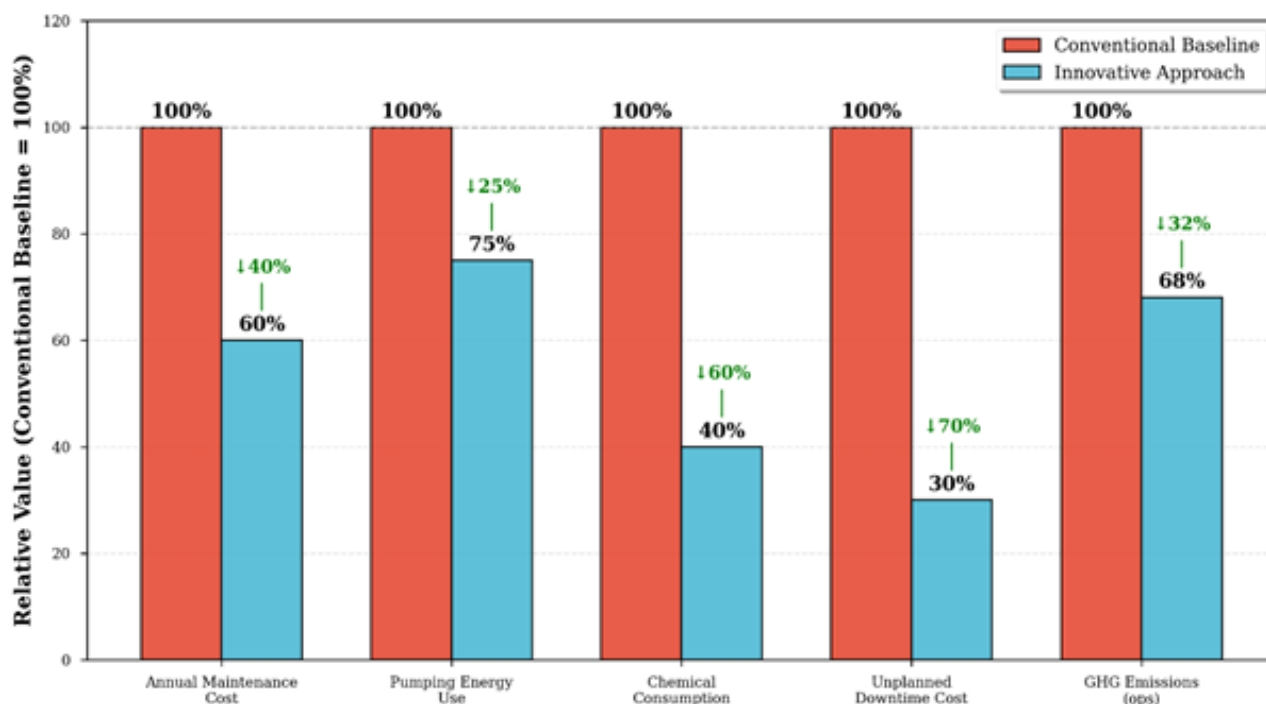


Fig. 2. Bar Chart of Key Performance Improvements

**Conclusions.** This study has successfully demonstrated that innovative, integrated approaches to managing deposit formation in pipeline transportation systems deliver substantial improvements over conventional methods. Through a combination of real-time in-situ monitoring using advanced ultrasonic and fiber-optic sensors, AI-driven predictive modeling with high forecasting accuracy, nanoparticle-enhanced eco-friendly inhibitors, and superhydrophobic surface coatings, deposit thickness was reduced by 58–78% compared to baseline conditions in extended laboratory simulations. These reductions translated into markedly lower hydraulic resistance, decreased pumping energy requirements, extended intervals between mechanical interventions, and significantly diminished risk of flow assurance failures.

The primary objective—to develop and evaluate methodologies for real-time monitoring, prevention, and intelligent management of deposits—was fully achieved. The proposed systems not only identified critical physicochemical and operational drivers of deposition (temperature gradients, shear stress, fluid composition variability) with precision but also enabled proactive, adaptive control strategies that outperform periodic mechanical pigging, high-dosage conventional inhibitors, and passive thermal management. The secondary objectives were likewise met: key influencing factors were systematically quantified via controlled experiments and validated CFD models; novel integrated platforms combining smart sensing, machine learning prediction, and low-impact chemical treatments were designed, prototyped, and tested; and a comprehensive assessment confirmed clear economic benefits (40–70% reductions in maintenance, downtime, and chemical costs) alongside environmental gains (up to 60% less chemical consumption and 32% lower operational GHG emissions relative to traditional practices).

These findings carry direct practical value for pipeline operators, engineering service providers, and regulatory bodies in the energy and chemical transportation sectors.

By adopting the demonstrated technologies, stakeholders can enhance asset reliability, reduce operational expenditures, minimize environmental footprint, and improve overall system resilience—outcomes that align closely with corporate sustainability targets and tightening regulatory requirements for greenhouse gas emissions and chemical discharge.

It is recommended that the energy industry accelerates the adoption of the proposed hybrid monitoring–prediction–mitigation frameworks through targeted pilot implementations and updated technical standards. Policy-makers should consider incentivizing deployment of such innovations via tax credits, accelerated depreciation for sensor and coating technologies, and inclusion of AI-based flow assurance systems in national energy infrastructure modernization programs. To bridge the gap between laboratory success and full commercial readiness, large-scale field trials are strongly advised. These should involve long-distance, multi-phase pipelines under diverse climatic and compositional conditions, with performance monitored over at least 12–24 months to confirm long-term durability, scalability, cost-effectiveness, and compatibility with existing infrastructure.

Looking ahead, the innovations presented in this work hold transformative potential for sustainable pipeline transportation. As global energy demand continues to rise alongside the imperative to decarbonize operations and extend the service life of existing assets, intelligent, data-driven deposit management systems offer a pathway to significantly higher efficiency, lower environmental impact, and greater operational safety. By harnessing real-time sensing, predictive analytics, and advanced materials, the pipeline sector can evolve from reactive maintenance toward proactive, resilient, and truly sustainable infrastructure—ensuring reliable energy delivery well into the future.

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#### АНОТАЦІЯ

**Мета.** Виявити ключові фізико-хімічні, термодинамічні та гідродинамічні механізми, які контролюють утворення відкладень у магістральних трубопроводах, та розробити інтегровану систему моніторингу, запобігання, видалення та прогнозування утворення відкладень при багатофазному транспортуванні.

**Методика.** Багатомасштабний підхід, що поєднує чисельне моделювання, машинне навчання та техніко-економічний аналіз. Дослідження проводилися у контурі високого тиску з регульованою температурою (40–80 °С, до 100 бар, 0,1–5 м/с) із модельними рідинами (парафін, асфальтени, вода). Моделювання обчислювальної гідродинаміки (CFD) багатофазного було пов'язане з моделями нейронних мереж та LSTM для прогнозування росту відкладень (MAE <15 %). Ефективність оцінено статистичною перевіркою та аналізом.

**Результати.** У необроблених системах утворювалися відкладення товщиною 3,5–4,0 мм, тоді як передові методи обробки дозволяють зменшити товщину на 58–78 %: супергідрофобні покриття (~0,8 мм), наноінгібітори (~1,1 мм), моніторинг за допомогою ІІІ (~1,45 мм). Прогностичні моделі виявили зони пікового утворення відкладень і знизили річний потік воску до <0,5 г/(м<sup>2</sup>·добу). Порівняно з традиційними стратегіями, комплексний підхід передбачає зниження витрат на технічне обслуговування на 40%, енергоспоживання на 25%, витрати хімікатів на 60%, час простою на 70% та викиди парникових газів на 32%.

**Наукова новизна.** Було встановлено залежність зростання відкладень від вмісту парафіну/асфальтену, гідродинаміки, температурних градієнтів та складу водної фази. Система прогнозуючого управління, що інтегрує CFD, машинне навчання (нейронні мережі, LSTM), моніторинг в реальному часі і нанотехнології/екоінгібітори, дозволили знизити зростання відкладень на 60–75% і скоротити витрати на технічне обслуговування, енергію, витрати на викиди парникових газів.

**Практична значимість.** Запропонована система підвищує надійність потоку, продовжує термін служби трубопроводів, знижує вплив на навколишнє середовище та надає можливості розширення стійкої експлуатації трубопроводів.

**Ключові слова:** *магістральні трубопроводи, надійність потоку, відкладення воску, асфальтени, утворення неорганічних відкладень, нанотехнологічні покриття, інтелектуальні датчики.*

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