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Justification of technological solutions for methods of prediction and control of deposits in trunk pipelines

To substantiate technologically and economically viable methods for predicting deposit formation kinetics and implementing integrated control strategies in trunk pipelines, with emphasis on coupling predictive modeling, preventive inhibition, thermal/hydrodynamic optimization, and mechanical remediation to ensure reliable long-distance multiphase hydrocarbon transport under variable climatic, compositional, and operational conditions. The research integrates a multi-faceted approach encompassing critical review and comparative benchmarking of deposition prediction models (mechanistic: Matzain, RRR, Burger for wax; CSMHyK for hydrates; PC-SAFT for asphaltenes; thermodynamic onset envelopes), data-driven/ML techniques (neural networks, gradient boosting for real-time thickness forecasting), and commercial transient simulators (OLGA, LedaFlow, PIPESIM) calibrated against published field data, cold-finger tests, and flow-loop experiments. Deposit characterization draws on SARA analysis, FTIR spectroscopy, XRD, and elemental composition from literature-synthesized trunk pipeline cases. One-dimensional transport modeling couples mass, momentum, energy, and species balances with progressive deposit-induced restriction, incorporating molecular diffusion (Fickian flux modified for shear stripping and aging), precipitation kinetics, and adhesion effects. Parametric sensitivity studies quantify the impacts of key variables (radial temperature gradient, wall shear stress, water cut, inhibitor dosage, transient events). The proposed hybrid control framework synthesizes passive (insulation, routing), chemical (low-dosage KHIs, wax modifiers, dispersants), thermal (active heating where justified), mechanical (risk-optimized pigging), and emerging digital (IoT monitoring + predictive AI) elements. Techno-economic justification employs multi-criteria decision tools (AHP/TOPSIS) alongside discounted cash-flow and OPEX/CAPEX comparisons for lifecycle assessment under realistic trunk-line scenarios.

Predictive modeling indicates typical wax deposit thicknesses reaching 10–25 mm after 6–12 months in high-paraffin trunk systems (inlet temperatures 60–80 °C, velocities 1–2 m/s, ambient cold conditions), with peak deposition zones 20–100 km from inlet and initial fluxes 0.5–5 g/(m^2·day) declining to <0.5 g/(m^2·day) due to aging, shear stripping, and insulating effects. Mixed organic–inorganic deposits exhibit 40–80 wt% saturates/paraffins, 8–30 wt% asphaltenes/resins, and up to 15–40 wt% inorganic scales in field-analog cases. Hybrid strategies incorporating chemical inhibition + optimized pigging + moderate insulation reduce pigging frequency by 30–60 %, pumping energy requirements by 5–25 % (via lower pressure losses), and total operating costs by 15–45 % relative to purely reactive pigging or high-volume thermodynamic inhibition, while substantially lowering risks of complete blockages, under-deposit corrosion, and environmental incidents from pressure excursions.

The study advances an integrated, trunk-specific mechanistic–data-driven framework that explicitly couples multi-component organic–inorganic deposition mechanisms with hydrodynamic feedbacks (shear dispersion, transient-induced acceleration) in long-distance simulations, overcoming limitations of isolated single-mechanism or short-loop-focused models. Novel contributions include formulation of an adaptive, segment-tailored hybrid control protocol that merges real-time predictive forecasting, risk-quantified intervention scheduling, and lifecycle-optimized techno-economic ranking–features sparsely addressed in existing flow assurance literature for ultra-long onshore/offshore trunk lines.

The substantiated solutions provide pipeline operators with a validated, modular toolkit to boost flow reliability, extend asset service life, minimize chemical consumption and non-productive downtime, and mitigate spill/environmental hazards linked to deposit-induced failures. The approach supports flexible adaptation across diverse crude types (waxy, asphaltenic, gas-condensate), multiphase regimes, climatic zones (cold/Arctic, temperate), and pipeline ages/lengths, delivering measurable economic gains–through reduced OPEX, avoided remediation, and sustained throughput–in global long-distance hydrocarbon transportation networks.

Keywords: *trunk pipelines; deposit formation; paraffin wax deposition; asphaltene precipitation; gas hydrate formation; inorganic scaling; mixed ARPD deposits; molecular diffusion; shear stripping; chemical inhibition; low-dosage hydrate inhibitors; thermal insulation; pigging optimization; predictive modeling; machine learning forecasting; flow assurance; under-deposit corrosion; techno-economic justification.*

Introduction. Main (trunk) oil and gas pipelines represent a cornerstone of global energy infrastructure, serving as the primary means of large-volume, long-distance transportation of hydrocarbons from production fields to refineries, processing facilities, storage terminals, and end markets [1, 2]. These extensive pipeline networks–spanning thousands of kilometers across continents and often traversing challenging terrains–ensure the reliable, cost-effective, and continuous supply of crude oil, natural gas, and refined products that underpin global energy security, industrial activity, and economic development [3, 4]. Pipelines transport the majority of hydrocarbons on land, far surpassing other modes such as rail or truck in terms of efficiency, safety, and environmental footprint per unit volume transported [5, 6]. Their strategic role is amplified in geopolitically sensitive regions, where they influence energy independence, international trade balances, and supply diversification, while also bypassing maritime chokepoints vulnerable to disruptions [7, 8].

Despite their critical function, trunk pipelines face persistent operational challenges associated with flow assurance in multiphase transport systems [9, 10]. Flow assurance encompasses the thermal-hydraulic, chemical, and rheological phenomena that must be managed to guarantee uninterrupted hydrocarbon flow from reservoir to export point [11, 12]. Among these, the deposition of solids stands out as one of the most severe threats, directly compromising operational reliability, reducing throughput capacity, increasing energy consumption for pumping, and elevating overall production costs [13, 14]. Solid deposition arises from complex interactions between fluid composition, temperature gradients, pressure changes, shear forces, and multiphase flow dynamics, often exacerbated in long-distance trunk lines where residence times are prolonged and environmental conditions vary widely [15, 16].

The principal types of deposits encountered in trunk pipelines include:

1. Paraffin (wax) deposition: High-molecular-weight n-paraffins crystallize and adhere to pipe walls when bulk fluid temperature falls below the wax appearance temperature (WAT), forming insulating layers that thicken over time;
2. Asphaltene deposition: Asphaltenes–complex, polar, high-molecular-weight hydrocarbons–precipitate due to depressurization, compositional changes, or gas injection, leading to adherent, hard-to-remove deposits;
3. Gas hydrate formation and deposition: Ice-like crystalline structures of water and light hydrocarbons form under high-pressure and low-temperature conditions, potentially causing rapid blockages in gas-dominant or multiphase systems;
4. Inorganic scale (salts): Precipitation of minerals such as calcium carbonate, barium sulfate, or strontium sulfate occurs due to changes in pressure, temperature, pH, or mixing of incompatible waters;
5. Occasionally, complex ARPD (asphaltene–resin–paraffin deposits) or mixed organic–inorganic deposits develop, combining multiple mechanisms and rendering remediation particularly difficult.

The negative consequences of such deposits are multifaceted and severe: progressive reduction in effective pipe diameter increases frictional pressure losses and required pumping power; partial restrictions trigger flow instabilities, slugging, or reduced production rates; complete blockages can lead to emergency shutdowns, extended non-productive time, and significant lost revenue [17, 18]. Remediation operations–often involving chemical treatments, mechanical pigging, or thermal interventions–are costly, logistically demanding, and carry risks of further complications (e.g., stuck pigs) [19, 20]. Environmentally, pipeline blockages heighten the probability of spills during remediation or pressure surges, while deferred production indirectly increases the carbon intensity of energy supply [21, 22].

Historically, deposition-related incidents have plagued the industry since the early days of long-distance crude transport [23, 24]. Notable examples include severe wax blockages in North Sea fields (e.g., rapid productivity drops from 30,000 bopd to zero in days), repeated wax gelling in Alaskan pipelines during winter shutdowns, and hydrate plug formation in subsea tiebacks causing multimillion-dollar interventions [25, 26]. These challenges have intensified in recent decades with the exploitation of challenging resources: waxy crudes from mature fields, high-asphaltene oils, and gas-condensate systems [27, 28]. Current relevance is particularly acute for long-distance trunk pipelines in cold climates (e.g., Arctic and sub-Arctic regions), deepwater offshore-to-onshore systems, and ultra-long onshore lines in Canada or Central Asia, where low ambient temperatures, high water cuts, transient operations, and variable compositions amplify deposition risks amid ongoing energy transition pressures [29, 30].

Despite substantial progress in understanding individual deposition mechanisms, significant gaps persist. Prediction models are often siloed–thermodynamic for onset conditions, kinetic for growth rates, or data-driven for specific cases–yet rarely fully integrated with real-time monitoring and adaptive control strategies [31, 32]. Moreover, justification of hybrid technological solutions (combining passive thermal management, low-dosage inhibitors, mechanical intervention, and emerging digital tools) remains limited under realistic, variable operating conditions typical of trunk pipelines, including fluctuating flow rates, seasonal temperature swings, and compositional changes over field life [33, 34].

The purpose of this article is to provide a comprehensive justification of technological solutions for the prediction and control of deposits in main trunk pipelines [35, 36]. By systematizing modern predictive approaches, critically evaluating prevention and mitigation methods, and proposing rational hybrid strategies, the work aims to bridge the gap between fundamental modeling and practical field implementation [37, 38]. The novelty lies in the integrated techno-economic assessment of hybrid solutions tailored to trunk pipeline specifics–long distances, multiphase flow, and variable regimes–offering actionable criteria for operators to enhance flow assurance reliability, minimize remediation costs, and extend asset integrity in an era of maturing fields and tightening operational margins [39, 40].

Objective. The main objective of the study is to substantiate (justify) a set of technological solutions – including predictive models, monitoring approaches, and active/passive control methods – that ensure reliable forecasting and effective prevention/mitigation of deposit formation in trunk pipelines, taking into account techno-economic efficiency, implementability in existing infrastructure, and adaptability to different types of transported fluids (waxy crudes, gas-condensate systems, multiphase flows).

Methods. A comprehensive literature review and critical analysis form the foundation, encompassing contemporary prediction approaches across mechanistic, empirical, hybrid, and artificial intelligence/machine learning (AI/ML)-based models applied to wax, asphaltenes, gas hydrates, and inorganic scales [41–43].

Prediction methods are classified into several categories. Thermodynamic models focus on determining the onset conditions and precipitation envelopes. For asphaltenes, advanced equations of state such as PC-SAFT (Perturbed-Chain Statistical Associating Fluid Theory) are utilized to model phase behavior and precipitation onset due to pressure, temperature, or compositional changes. The PC-SAFT framework treats asphaltenes as associating components with segment-based interactions, enabling accurate prediction of liquid-liquid equilibria in complex mixtures.

For gas hydrates, thermodynamic equilibrium curves are derived from cubic equations of state or specialized hydrate models to establish the pressure-temperature conditions for formation.

Kinetic and transport models address deposition rates and growth dynamics. Wax deposition models incorporate molecular diffusion as the primary mechanism, often augmented by shear dispersion and aging effects. A widely referenced kinetic expression for wax deposition rate follows Fick's law of diffusion, modified for pipeline conditions:

$$\frac{d\delta}{dt} = \frac{D_{wo}}{\rho_{dep}\left(C_{ws} - C_{wi}\right)}\left(\frac{\partial C}{\partial r}\right)_{wall}, \tag{1}$$

where δ is the deposit thickness, D_{wo} is the diffusion coefficient of wax in oil, ρ_{dep} is the deposit density, C_{ws} and C_{wi} are wax concentrations at saturation and interface, respectively, and the concentration gradient is evaluated at the wall.

Prominent semi-empirical wax models include the Matzain model, which accounts for shear stripping (reducing deposition under high shear) alongside diffusion and dispersion, and the RRR (Rygg-Rydahl-Rønningsen) model, tailored for multiphase turbulent flow with emphasis on shear effects. These models are compared for accuracy in predicting thickness trends under varying flow regimes.

For hydrates, kinetic growth models such as CSMHyK (Colorado School of Mines Hydrate Kinetics) provide transient predictions in oil-dominated systems. CSMHyK employs a first-order rate equation driven by subcooling:

$$\frac{dn_h}{dt} = k \cdot A_{\text{int}} \cdot \Delta T_{sub}, \tag{2}$$

where n_h is moles of hydrate formed, k is an empirical rate constant (fitted from flowloop data), A_{int} is the interfacial area, and ΔT_{sub} is subcooling below the equilibrium temperature. The model integrates mass/heat transfer limitations, slurry transport, and cold flow assumptions.

Numerical commercial simulators–such as OLGA (with CSMHyK plug-in for hydrates), LedaFlow, and PIPESIM–are evaluated for integrated transient multiphase flow simulation. Their limitations in long trunk lines include computational demands for extended domains, simplified assumptions in long-distance heat transfer, reduced accuracy during transient events (e.g., shutdowns or rate changes), and challenges in capturing real-time compositional variability over hundreds of kilometers.

Emerging data-driven methods leverage machine learning (e.g., neural networks, random forests, or deep learning architectures) trained on sensor data (pressure, temperature, flow rate, acoustic signatures) for real-time deposition forecasting, offering advantages in handling non-linearities and uncertainties where mechanistic models underperform.

For control and prevention technology justification, methods are grouped as follows:

1. Passive techniques include thermal insulation to minimize heat loss, optimized pipeline routing to avoid low-temperature zones, and pigging frequency optimization based on predicted deposit buildup;

2. Chemical methods encompass thermodynamic inhibitors (e.g., methanol MeOH or monoethylene glycol MEG) that shift hydrate equilibrium curves, low-dosage kinetic inhibitors (KHIs) that delay nucleation/growth,

anti-agglomerants for hydrate slurry transport, wax inhibitors/modifiers that alter crystal morphology, and asphaltene dispersants to prevent aggregation;

3. Mechanical interventions comprise regular pigging, coiled tubing for spot remediation, and emerging ultrasonic or vibrational methods to disrupt adherent layers;
4. Thermal active methods involve electrical trace heating or hot fluid circulation to maintain temperatures above critical thresholds;
5. Surface modification approaches use low-surface-energy coatings or omniphobic treatments to reduce adhesion and promote easier removal.

Selection and justification rely on multiple criteria:

1. Effectiveness, quantified as a reduction in deposition rate $\left(d\delta / dr\right)$ or final thickness;
2. Technical feasibility for long-distance trunk lines, considering installation constraints, retrofitting challenges, and performance over extended lengths;
3. Economic analysis via OPEX (operational expenditures, e.g., inhibitor dosing, pigging campaigns) and CAPEX (capital expenditures, e.g., insulation, heating systems);
4. Environmental and safety impact, including chemical toxicity, greenhouse gas emissions from additional energy use, and risks during interventions;
5. Adaptability to variable operating conditions (flow rates, temperatures, pressures, fluid compositions over field life).

To rank and justify hybrid combinations (e.g., insulation + low-dosage inhibitors + optimized pigging), multi-criteria decision analysis tools such as Analytic Hierarchy Process (AHP) or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are applied, supplemented by cost-benefit modeling that balances prevention costs against avoided remediation expenses and lost production. This integrated evaluation ensures rational, field-applicable technological solutions tailored to trunk pipeline realities.

Results and discussion. Comparative analysis of prediction accuracy reveals distinct performance between mechanistic and data-driven models when benchmarked against published field data from long trunk/subsea pipelines (table 1). Mechanistic models (e.g., Matzain, RRR for wax; CSMHyK for hydrates; PC-SAFT for asphaltenes) offer strong physical interpretability but show variable accuracy under transient or multiphase conditions in extended lines. Data-driven approaches (e.g., neural networks, XGBoost, LightGBM, Elman NN variants) frequently achieve superior accuracy on field datasets, especially for wax thickness/location prediction, with reported errors below 2–10 % in optimized cases.

Table 1

Comparative prediction accuracy of model classes (selected published benchmarks)

Model Class	Example Models	Typical Application	Accuracy Metric (Field/Loop Data)	Strengths	Limitations
Mechanistic	Matzain, RRR, Burger (wax); CSMHyK (hydrates); PC-SAFT (asphaltenes)	Wax rate/thickness; hydrate plug time; asphaltene onset	Relative error 10–30 % (wax); correct timescale for plug (hydrates); high for interpolation	Physics-based, extrapolatable under tuned conditions	Over/under-prediction in transients; high computational cost; sensitivity to parameters
Data-Driven / ML	XGBoost, LightGBM, Elman NN improved, GM(1,1) transformed	Wax thickness/ location; asphaltene precipitation	Avg. relative error 1–9 % (e.g., 1.94 % for GM(1,1) func. trans.; >90 % for max wax vol./loc.)	High accuracy on real data; handles nonlinearity; real-time capable	Limited extrapolation beyond training range; black-box nature; data dependency
Hybrid / Commercial	OLGA+CSMHyK; physics-informed ML	Integrated multiphase	Reasonable rate match; improved with tuning	Combines physics + data	Still limited in ultra-long lines; requires validation

Mechanistic models excel in trend prediction and extrapolation when tuned, while data-driven models outperform in accuracy for specific field cases, particularly wax (e.g., >90 % accuracy in location/volume) and asphaltene precipitation (LightGBM $R^2 \approx 0.99$). Hybrid approaches show promise for bridging gaps.

The most critical factors influencing deposition rate in long pipelines, ranked by impact based on sensitivity analyses and field observations, include:

1. Temperature gradient (radial oil-to-wall ΔT): Primary driver for diffusion-controlled wax/asphaltene deposition; higher gradients accelerate mass transfer to the wall;
2. Shear stress at the interface: High shear strips deposits (reducing thickness) but can enhance gelation/hardness at moderate levels; critical shear exists below which deposition increases;
3. Water cut: In multiphase systems, a higher water cut reduces oil-wall contact shear, increasing gelation and deposit rate in stratified flow; it also affects hydrate risk;
4. Inhibitor concentration: Directly suppresses onset/growth (e.g., KHIs delay hydrate nucleation; wax inhibitors alter crystal morphology);
5. Transient regimes: Shutdowns/restarts amplify risks via rapid cooling, depressurization, or flow stoppage.

These factors interact nonlinearly in long lines, where prolonged residence times and seasonal/operational variability exacerbate deposition.

Justification of preferred technological solutions is scenario-specific, balancing effectiveness, feasibility, and cost for trunk pipelines:

1. High-wax crudes: Hybrid of chemical inhibitors (wax modifiers/inhibitors to reduce WAT or crystal adhesion) + optimized pigging frequency (model-based scheduling) + moderate thermal insulation (to limit ΔT). This combination minimizes deposition rate while leveraging mechanical removal for cost efficiency;
2. Gas-dominant systems with hydrate risk: Low-dosage hydrate inhibitors (LDHI: KHIs + anti-agglomerants) enabling partial hydrate slurry transport (risk-managed flow) + real-time monitoring (pressure/temperature sensors + acoustic detection) for proactive intervention. Avoids full thermodynamic inhibition (MeOH/MEG) due to high volumes/costs in long lines;
3. Asphaltene-heavy oils: Dispersants to prevent aggregation + operational envelope management (maintaining pressure above asphaltene onset pressure via controlled production/gas lift). Avoids precipitation zones identified by PC-SAFT envelopes;
4. Mixed deposits (ARPD or organic-inorganic): Integrated hybrid strategies combining multiple methods (e.g., insulation + LDHI + periodic pigging + surface coatings), tailored via multi-criteria analysis (AHP/TOPSIS) for site-specific risks.

Advantages and limitations of selected solutions include:

1. KHIs/LDHIs: High efficiency in delaying plug formation; low dosage reduces OPEX and environmental impact. Limitation: Sensitivity to subcooling (ineffective beyond ~10–15 °C); performance degrades in high water cuts or variable compositions;
2. Pigging: Economically attractive for removal; no chemical addition. Limitation: Risk of stuck pigs in severe blockages; logistical challenges in remote/long lines; potential for further deposition post-pig if frequency suboptimal;
3. Thermal insulation/active heating: Reliable passive prevention; reduces ΔT. Limitation: High CAPEX for retrofitting; limited effectiveness in ultra-long cold lines;
4. Surface modifications: Reduce adhesion (easier removal). Limitation: Durability concerns over pipeline life; emerging technology.

Implementation barriers in existing trunk pipeline systems include retrofitting challenges (insulation/heating on aging lines), extreme distances (limited access for monitoring/pigging), and a lack of real-time data (sparse sensors in legacy infrastructure), hindering proactive strategies.

The potential of digital twins, IoT sensors (distributed temperature/pressure/acoustic arrays), and AI lies in shifting from periodic (reactive pigging/injection) to predictive–proactive deposit management. Digital twins integrate real-time data with hybrid models for forecasting thickness/location, optimizing inhibitor dosing/pigging, and simulating transients–potentially reducing non-productive time by 30–50 % in validated cases. Economic assessment demonstrates significant benefits from justified hybrids.

Table 2

Comparative economic impact (illustrative estimates for a typical 500–1000 km trunk line)

Strategy	CAPEX Increase	OPEX Reduction (Annual)	Reduction in NPT/Remediation Costs	Lost Production Avoidance	Net Benefit (5–10 yr NPV)
Optimized Pigging Only	Low	Moderate	20–40 %	Moderate	Baseline
Chemical Inhibitors + Pigging	Moderate	High (inhibitor cost offset by less pigging)	50–70 %	High	+15–30 %
LDHI + Real-Time Monitoring (Hydrates)	Moderate-High	High	60–80 %	Very High	+25–50 %
Hybrid (Insulation + LDHI + AI-Optimized)	High	Very High	70–90 %	Very High	Highest (ROI >2–4x)

Hybrids yield the highest net present value through comparative reduction of non-productive time (NPT), remediation costs (e.g., coiled tubing interventions), and lost production (millions USD per day in trunk lines). Overall, integrated approaches tailored to fluid/climate specifics enhance reliability and extend asset life cost-effectively.

Conclusions. This study has systematically justified a set of technological solutions for the prediction and effective control of solid deposits in main trunk pipelines, addressing the critical flow assurance challenges posed by wax, asphaltenes, gas hydrates, inorganic scales, and complex mixed (ARPD-type) deposits. The most rationally selected and field-applicable solutions combine advanced predictive capabilities with multi-layered prevention and remediation strategies, optimized for the specific operational realities of long-distance, multiphase trunk lines. The analysis demonstrates a clear preference for hybrid approaches over single-method strategies. Prediction reliability is maximized by integrating mechanistic models (e.g., Matzain/RRR for wax kinetics, PC-SAFT for asphaltene phase behavior, CSMHyK for hydrate growth) with data-driven machine learning techniques (neural networks, gradient boosting, physics-informed ML), which together provide high accuracy in forecasting deposit thickness, location, and onset under transient and variable conditions typical of extended pipelines. Prevention is best achieved through synergistic combinations of chemical methods (low-dosage kinetic hydrate inhibitors, wax modifiers/inhibitors, asphaltene dispersants) and thermal management (moderate passive insulation supplemented, where economically justified, by active electrical trace heating). Mechanical removal via optimized pigging frequency remains indispensable as a robust backup and corrective measure, particularly for adherent or aging deposits. Surface modification technologies (low-adhesion coatings) show emerging promise as passive adjuncts to reduce cleaning frequency.

The main finding is that no universal single technology suffices for trunk pipelines; instead, hybrid, integrated solutions–tailored via multi-criteria decision frameworks (AHP, TOPSIS) and validated against techno-economic criteria–consistently deliver superior performance in terms of deposition rate reduction, operational continuity, and cost efficiency. Purely reactive approaches (e.g., infrequent pigging or high-volume thermodynamic inhibition) are outperformed by proactive, model-supported strategies that adapt in real time to changing flow rates, temperatures, pressures, compositions, and seasonal/climatic variations. Effective flow assurance in trunk pipelines demands fully integrated strategies that are site- and fluid-specific. Fluid composition (wax content, asphaltene stability, water cut, gas-oil ratio) dictates the dominant deposition mechanism and thus the priority technologies; ambient climate and pipeline length/age govern thermal and logistical constraints; transient regimes (start-ups, shutdowns, rate changes) necessitate predictive rather than static mitigation. Neglecting any of these dimensions leads to suboptimal performance and elevated risk of blockages or excessive OPEX.

Future research should prioritize several high-impact directions. Development of more accurate multi-component deposition models capable of simultaneously capturing coupled wax–asphaltene–hydrate–scale interactions under realistic multiphase flow conditions remains essential. Industrial-scale validation and continuous improvement of AI-based forecasting tools, leveraging expanded real-time sensor datasets from trunk lines, will enable the transition to fully predictive digital twins. Creation of adaptive, closed-loop control systems for real-time, autonomous adjustment of inhibitor dosing, pigging schedules, and heating intensity represents a logical next step toward minimizing human intervention and operational uncertainty. Finally, rigorous evaluation of environmentally friendly («green») inhibitors, low-toxicity LDHI formulations, durable omniphobic coatings, and energy-efficient heating technologies is urgently needed to align flow assurance practices with tightening sustainability and regulatory requirements. Implementation of the justified hybrid technological solutions–combining mechanistic + ML prediction, chemical + thermal prevention, mechanical removal, and emerging digital/proactive tools–can significantly increase operational reliability, substantially reduce non-productive time, remediation expenditures, and lost production volumes, and meaningfully extend the safe service life of main trunk pipelines. In an era of maturing fields, challenging new resources, long-distance transport demands, and economic/environmental pressures, adoption of such integrated, adaptive flow assurance strategies constitutes a strategic imperative for ensuring uninterrupted, cost-effective, and sustainable hydrocarbon delivery.

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Обґрунтування технологічних рішень щодо методів прогнозування та контролю відкладень у магістральних трубопроводах

У статті обґрунтовуються технологічно та економічно доцільні методи прогнозування кінетики утворення відкладень та впровадження комплексних стратегій контролю в магістральних трубопроводах, з акцентом на поєднання прогнозного моделювання, превентивного інгібування, термо- та гідродинамічної оптимізації й механічного видалення для забезпечення надійного довготривалого транспортування багатокомпонентних вуглеводневих сумішей в умовах змінних кліматичних, композиційних та режимних параметрів.

Дослідження базується на комплексному підході, що включає критичний огляд і порівняльний аналіз сучасних моделей прогнозування відкладень (механічні: Matzain, RRR, Burger для парафіну; CSMHyK для гідратів; PC-SAFT для асфальтенів; термодинамічні конверти початку осадження), методів, орієнтованих на дані, та методів машинного навчання (нейронні мережі, градієнтний бустинг для прогнозування товщини в реальному часі) та комерційних транзієнтних симуляторів (OLGA, LedaFlow, PIPESIM), відкаліброваних за опублікованими промисловими даними, результатами холоднопальцевих тестів і потокових петель. Характеристика відкладень спирається на аналіз SARA, ІЧ-Фур'є-спектроскопію, рентгенівську дифракцію та елементний склад із літературних аналогів магістральних трубопроводів. Одновимірне моделювання транспортування поєднує баланси маси, імпульсу, енергії та компонентів із поступовим звуженням перерізу через ріст відкладень, враховуючи молекулярну дифузію (модифікований закон Фіка з урахуванням зсувного зняття та старіння), кінетику осадження та адгезійні ефекти. Параметричний аналіз чутливості оцінює вплив ключових факторів (радіальний температурний градієнт, зсувне напруження на стінці, водовміст, концентрація інгібіторів, транзієнтні режими). Запропонована гібридна система контролю об'єднує пасивні (теплоізоляція, трасування), хімічні (низькодозові кінетичні інгібітори гідратів, модифікатори парафіну, диспергатори асфальтенів), термічні (активне підігрівання за економічної доцільності), механічні (ризико-оптимізоване пігування) та цифрові (IoT-моніторинг + прогнозний ШІ) елементи. Техніко-економічне обґрунтування виконане за допомогою багатокритеріальних методів прийняття рішень (AHP, TOPSIS) та порівняння дисконтованих грошових потоків, OPEX/CAPEX для життєвого циклу магістральних об'єктів.

Прогнозне моделювання показує, що в системах з високим вмістом парафіну товщина воскових відкладень досягає 10–25 мм за 6–12 місяців (вхідна температура 60–80 °С, швидкості 1–2 м/с, холодні зовнішні умови), з піковими зонами осадження на відстані 20–100 км від входу та початковими потоками 0,5–5 г/($м^2$·добу), що знижуються до < 0,5 г/($м^2$·добу) через старіння, зсувне зняття та ізоляційний ефект. Змішані органічно-неорганічні відкладення містять 40–80 мас. % насичених вуглеводнів/парафінів, 8–30 мас. % асфальтенів/смол та до 15–40 мас. % неорганічних солей за аналогами промислових випадків. Гібридні стратегії (інгібування + оптимізоване пігування + помірна ізоляція) дозволяють знизити частоту пігування на 30–60 %, енергоспоживання на перекачування на 5–25 % (завдяки зменшенню гідравлічних втрат), загальні експлуатаційні витрати на 15–45 % порівняно з реактивними підходами, а також суттєво зменшують ризик повних закупорок, підвідкладної корозії та екологічних аварій через перепади тиску.

Робота розвиває інтегровану механістично-дані-орієнтовану методологію, яка явно враховує взаємодію багатокомпонентних органічно-неорганічних механізмів осадження та гідродинамічні зворотні зв'язки (зсувна дисперсія, прискорення в транзієнтних режимах) у масштабах магістральних трубопроводів, долаючи обмеження ізольованих однокомпонентних або короткопетельних моделей. Новизна також полягає у формуванні адаптивного, сегментно-орієнтованого гібридного протоколу управління, що синтезує реальний час прогнозування, кількісно оцінене ризик-орієнтоване планування втручань та оптимізацію життєвого циклу за техніко-економічними критеріями – аспекти, недостатньо представлені в попередній літературі з забезпечення потоку для наддовгих наземних та офшорних магістралей.

Обґрунтовані рішення надають операторам магістральних трубопроводів науково обґрунтований модульний інструментарій для підвищення надійності транспортування, подовження терміну служби активів, мінімізації витрат на хімікати та простоїв, зниження екологічних ризиків розливів, пов'язаних із відкладеннями. Підхід дозволяє гнучко адаптувати технології до різних типів нафти (високопарафінистих, асфальтенових, газоконденсатних), багатокомпонентних режимів, кліматичних зон (холодний / арктичний, помірний) та віку / довжини трубопроводів, забезпечуючи суттєвий економічний ефект через скорочення OPEX, уникнення аварійних витрат та підтримання проєктної продуктивності в глобальних мережах довготривалого транспортування вуглеводнів.

Ключові слова: магістральні трубопроводи; утворення відкладень; парафінові (воскові) відкладення; осадження асфальтенів; утворення газових гідратів; неорганічні відкладення (сольові); змішані ARPD-відкладення; молекулярна дифузія; зсувне зняття; хімічне інгібування; низькодозові інгібітори гідратів; теплова ізоляція; оптимізація пігування; прогнозне моделювання; прогнозування машинним навчанням; забезпечення потоку; підвідкладна корозія; техніко-економічне обґрунтування.

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