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Research on Wax Deposition Characteristics and Mitigation Strategies in Submarine Oil and Gas Multiphase Flow Pipelines

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Abstract **Review Article**

This paper investigates the characteristics of wax deposition in multiphase flow within submarine oil and gas pipelines and proposes corresponding mitigation and control strategies. It begins by outlining the definition and classification of multiphase flow, highlighting the specific characteristics and challenges faced by submarine pipelines, such as wax deposition and hydrate formation. Subsequently, the causes, influencing factors, properties, and structural characteristics of wax deposits are analyzed in depth. The impact of wax deposition on pipeline flow is discussed, including increased flow resistance, reduced throughput, and potential pipeline blockage. To address these challenges, the paper proposes mitigation strategies and technical methods, including preventive measures like optimized pipeline design, controlled oil-gas mixture ratios, and the addition of inhibitors, as well as removal techniques such as hot water flushing, solvent cleaning, and high-pressure air blowing. Furthermore, the importance of pipeline maintenance and monitoring is emphasized, recommending the adoption of intelligent monitoring systems for real-time wax deposition monitoring and early warning. Finally, the research findings and contributions are summarized, future research directions are outlined, suggesting further in-depth study of practical applications of wax deposition issues and exploration of novel mitigation technologies and methods to enhance the safety and stability of submarine oil and gas pipelines.

Keywords: Wax Deposition, Submarine Pipelines, Multiphase Flow, Mitigation Strategies, Intelligent Monitoring.

1. INTRODUCTION

1.1 Research Background and Significance

As crucial facilities for offshore oil and gas extraction and transportation [1], the safe and stable operation of submarine oil and gas pipelines is of great significance for ensuring national energy security and promoting economic development. During the transportation process in submarine pipelines, wax components within the crude oil can deposit under high-pressure and potentially lower-temperature conditions, leading to pipeline blockages, reduced flow rates, and even safety incidents. This persistent challenge has long troubled the offshore oil and gas extraction and transportation industry and has attracted significant attention from both academia and engineering sectors.

From the research background perspective, studying the characteristics and mitigation strategies of wax deposition in submarine multiphase flow is crucial for ensuring the safe and stable operation of these pipelines. Through in-depth research into the mechanisms and characteristics of multiphase wax deposition, we can better understand this complex phenomenon and provide a scientific basis for formulating effective mitigation strategies. This research can also offer technical support for the development and utilization of offshore oil and gas resources, promoting the sustainable development of the offshore oil and gas industry.

From the research significance perspective, this study helps to deeply reveal the mechanisms and characteristics of wax deposition in submarine multiphase flow, providing a scientific basis for developing effective mitigation strategies. Simultaneously, this research can also provide technical support for the development and utilization of offshore oil and gas resources, promoting the sustainable development of the offshore oil and gas industry.

1.2 Domestic and International Research Status and Trends

Research on the characteristics and mitigation strategies of wax deposition in submarine multiphase flow pipelines is particularly important during the extraction and transportation of offshore oil and gas resources. In recent years, certain progress has been made in this field both domestically and internationally.

Domestically (within China), with increasing emphasis on the safe operation of submarine pipelines, research on multiphase wax deposition characteristics and mitigation strategies has gradually increased. For example, China National Offshore Oil Corporation (CNOOC) has conducted in-depth research on wax deposition characteristics in submarine pipeline projects, revealing the deposition patterns of wax crystals under certain conditions through simulation experiments and data analysis. To effectively address the wax deposition problem, domestic researchers have also proposed some mitigation strategies, such as using chemical wax inhibition and mechanical wax removal, to reduce the accumulation of wax crystals within pipelines. However, due to the complex and variable submarine environment and the involvement of complex physical processes like multiphase flow, the mechanisms of wax deposition are not yet fully understood, and mitigation strategies require further optimization and improvement.

Internationally, research on the characteristics and mitigation strategies of wax deposition in submarine multiphase flow pipelines is relatively more mature. Foreign scholars have conducted in-depth studies on the mechanisms and characteristics of wax deposition. Using advanced experimental techniques and numerical simulation methods, they have revealed the movement patterns and deposition characteristics of wax crystals within pipelines. There is also a focus internationally on applying new technologies and materials to the field of wax deposition mitigation in submarine pipelines, such as using smart sensors and automated control systems for real-time monitoring and timely removal of wax crystals within pipelines. The application of these technologies has improved the operational efficiency of submarine pipelines and reduced the accident rate caused by wax deposition.

Research on the characteristics and mitigation strategies of wax deposition in submarine multiphase flow will increasingly emphasize the combination of theory and practice. By strengthening experimental and numerical simulation research, new theories and methods regarding wax deposition characteristics and mitigation strategies will be revealed. As the development of offshore oil and gas resources intensifies, the importance of wax deposition mitigation in submarine pipelines will become more prominent. In the future, scholars both domestically and internationally will continue to dedicate efforts to research in this field, contributing to enhancing the operational efficiency and safety stability of submarine pipelines [2].

1.3 Research Content and Methodology

This study is dedicated to deeply exploring the characteristics of wax deposition in submarine multiphase flow pipelines, aiming to reveal its underlying mechanisms and propose effective mitigation strategies. To achieve this goal, we have meticulously designed the research content [3] and adopted multiple research methods to ensure the comprehensiveness and depth of the study.

In terms of content, we will focus on the characteristics and mitigation strategies of wax deposition in submarine multiphase flow pipelines. Specifically, we will prioritize researching the mechanisms of wax deposition, using a combination of experiments and numerical simulations to deeply analyze the behavior of wax deposition under different operating conditions. We will also study the formulation and effectiveness evaluation of mitigation strategies. By comparing experimental data with simulation results, we will reveal the effectiveness of different mitigation strategies in practical applications, providing strong support for optimizing these strategies. Additionally, we will pay attention to the application prospects of new technologies and materials in the field of wax deposition mitigation. By investigating the latest technological advances, we aim to inject new vitality into the field of wax deposition mitigation and promote continuous innovation and development of related technologies.

In terms of research methods, we will employ various approaches such as theoretical analysis, experimental research, and numerical simulation. Through theoretical analysis, we will reveal the intrinsic mechanisms of wax deposition; through experimental research, we will obtain actual data on wax deposition, providing strong support for theoretical analysis; through numerical simulation, we will uncover the evolution patterns of wax deposition, providing a scientific basis for formulating mitigation strategies. The comprehensive use of multiple methods will ensure the high accuracy and reliability of our research.

In terms of the technical roadmap, we will start with a literature review to understand the research progress and achievements in related fields. Based on this, we will design and conduct experiments to obtain first-hand data. Through numerical simulation and data analysis, we will reveal the characteristics of wax deposition and the effectiveness of mitigation strategies. Finally, we will formulate and evaluate the effectiveness of mitigation strategies, providing strong support for practical application. The implementation of this technical roadmap will ensure the high feasibility and practicality of our research.

2. OVERVIEW OF MULTIPHASE FLOW IN SUBMARINE PIPELINES

2.1 Definition and Classification of Multiphase Flow

Multiphase flow, as an important branch of fluid mechanics, has wide applications in various fields such as petroleum, chemical engineering, metallurgy, and power generation. The presence of multiphase flow is even more common in submarine oil and gas pipelines, significantly impacting the safe operation and efficiency improvement of pipelines. This section will elaborate on the definition and classification of multiphase flow.

Multiphase flow refers to a flowing mixture composed of two or more different substances, which may exist in different physical states, such as solid, liquid, or gaseous. In submarine oil and gas pipelines, due to changes in conditions like pressure and temperature, as well as factors like the solubility of various components in crude oil, the phenomenon of multiphase flow is particularly prominent. To study multiphase flow more effectively, it can be classified into the following categories based on the combination of phases:

Gas-liquid two-phase flow is a common form of flow in the petroleum industry. During extraction and transportation, due to reasons such as pressure drop, temperature decrease, or changes in crude oil composition, gas may evolve from the liquid, forming gas-liquid two-phase flow. This flow form is particularly common in submarine oil and gas pipelines and significantly impacts the safe operation and efficiency of pipelines. The formation of gas-liquid two-phase flow may lead to problems such as pressure fluctuations and flow instability within the pipeline, thereby affecting the normal operation of the pipeline.

Liquid-solid two-phase flow is another common form of multiphase flow. In the petroleum industry, liquid-solid two-phase flow mainly exists during the extraction, treatment, and transportation of crude oil. Due to the presence of solid materials such as sand and particles in crude oil, when the liquid flows, these solids are carried along with the liquid, forming liquid-solid two-phase flow. The formation of liquid-solid two-phase flow may lead to problems such as blockages and wear within the pipeline, thereby affecting the operational efficiency and safety of the pipeline.

Gas-solid two-phase flow is a special form of multiphase flow. In the petroleum industry, gas-solid two-phase flow mainly exists during the extraction, treatment, and transportation of crude oil. Due to the presence of gas and solid materials in crude oil, when the gas flows, these solids are carried along with the gas, forming gas-solid two-phase flow. The formation of gas-solid two-phase flow may lead to problems such as blockages and wear within the pipeline, thereby affecting the operational efficiency and safety of the pipeline.

The application of multiphase flow in the petroleum industry is extensive and complex. To effectively address the challenges posed by multiphase flow, the petroleum industry needs to continuously strengthen the research, development, and application of related technologies to improve the transportation efficiency and safety of pipelines [4].

2.2 Characteristics and Challenges of Submarine Pipelines

As an important component of offshore energy development, the characteristics and challenges of submarine oil and gas pipelines cannot be ignored. Pipelines are located on the seabed, an extremely unique operating environment where they must withstand factors such as seawater pressure, corrosion, and vibration, all of which pose potential threats to the safety and stability of the pipelines.

The characteristics of submarine oil and gas pipelines are mainly reflected in their complex operating environment and extreme process conditions. Pipelines need to withstand enormous pressure from seawater, especially as depth increases, pressure gradually rises, placing higher demands on the strength and stability of the pipeline. Corrosive substances in seawater cause long-term erosion of the pipeline, leading to gradual thinning of the pipe wall and affecting its load-bearing capacity. Changes in the speed and direction of seabed currents can also cause strong impacts and vibrations on the pipeline, thereby affecting its safe operation.

During the operation of submarine oil and gas pipelines, the complex characteristics of multiphase flow also present significant challenges. Multiphase flow refers to the phenomenon where substances containing gas, liquid, and solid phases flow simultaneously within the pipeline. This flow state may lead to unstable flow forms such as flow separation and vortices within the pipeline. In vortex regions, due to faster fluid velocity and lower pressure, pipeline leaks or ruptures may occur. Challenges such as wax deposition and hydrate formation also need to be faced during the transportation process in submarine pipelines. These problems may affect the safe operation and efficiency of the pipeline, even leading to economic losses and environmental pollution.

To address these challenges and risks, the design and maintenance of submarine oil and gas pipelines require strict quality control and technological innovation. This includes using advanced materials and processes to improve the strength and corrosion resistance of pipelines; optimizing pipeline layout and setting reasonable compensation measures to reduce vibration and displacement during operation; and implementing real-time monitoring and early warning mechanisms to promptly discover and resolve potential safety hazards [5].

2.3 Application of Multiphase Flow in Submarine Pipelines

In submarine oil and gas pipeline systems, multiphase flow, as a complex fluid motion phenomenon, plays a crucial role in pipeline design, operation, and safety assessment. Submarine oil and gas pipelines transport oil and gas resources through multiphase flow, with gas-liquid two-phase flow being the primary transportation method. This flow method has significant characteristics, such as uneven velocity distribution and large pressure losses, which directly impact the operational stability and safety of the pipeline.

In terms of transportation methods, submarine oil and gas pipelines mainly use gas-liquid two-phase flow for transport. Due to the complexity of the marine environment, such as changes in seawater depth, temperature, and salinity, the flow characteristics of multiphase flow within the pipeline also exhibit complex and variable features. To cope with this complexity, pipeline designers need to fully understand the flow characteristics of multiphase flow to optimize pipeline design and ensure stable pipeline operation.

In terms of flow characteristics, multiphase flow exhibits unique behaviors in submarine pipelines. Due to varying water depths, pressure changes accordingly, leading to an uneven distribution of flow velocity within the pipeline for multiphase flow. In high-pressure zones, the flow velocity of multiphase flow is faster, while in low-pressure zones, it is relatively slower. The pressure loss of multiphase flow within the pipeline also shows significant differences. In high-pressure zones, due to the faster flow velocity, the pressure loss is relatively larger, while in low-pressure zones, it is relatively smaller. These characteristics significantly impact the operational efficiency and safety of the pipeline.

Addressing the characteristics and challenges of multiphase flow in submarine pipelines requires formulating effective mitigation strategies. This can be achieved by optimizing pipeline design to improve flow efficiency and stability, and strengthening monitoring and maintenance work to promptly discover and resolve problems within the pipeline. Through the implementation of these measures, the safe and stable operation of submarine oil and gas pipelines can be ensured [7].

3 WAX DEPOSITION CHARACTERISTICS AND IMPACT ANALYSIS

3.1 Causes and Influencing Factors of Wax Deposition

Wax deposition is a common phenomenon in pipelines carrying waxy crude oil during operation. Its formation is related to various factors such as crude oil properties, temperature, pressure, and flow velocity.

The wax content in crude oil is an important factor affecting wax deposition. Wax molecules in crude oil can maintain certain mobility at suitable temperatures, but once the temperature decreases, these molecules aggregate together, forming wax crystals. Crude oil with higher wax content forms a greater number of wax crystals, thereby increasing the risk of wax deposition.

Temperature change is a key trigger for wax deposition. As the temperature decreases, the movement speed of wax molecules in crude oil gradually slows down, and the intermolecular interaction forces increase, leading to the formation and deposition of wax crystals. Temperature fluctuations and instability are also important factors causing wax deposition.

Pressure changes also have a certain impact on the formation of wax deposition. Changes in pressure affect the volume and fluidity of crude oil, thereby influencing the formation of wax deposition. When pressure increases, the volume of crude oil expands, and fluidity worsens, thus increasing the risk of wax deposition.[8]

Flow velocity also significantly affects wax deposition. Both excessively high and low flow velocities may lead to the formation of wax deposition. When the flow velocity is too high, it can disrupt the oil-water interface, dispersing wax crystals into the oil phase and forming a stable suspension system; whereas when the flow velocity is too low, wax crystals easily form deposits on the inner wall of the pipeline, increasing the flow resistance.

3.2 Properties and Structural Characteristics of Wax Deposits

In terms of the composition of wax deposits, the main body consists of wax components, which mostly originate from solid hydrocarbons like paraffin wax and microcrystalline wax in crude oil. When the temperature of crude oil drops below the wax appearance point (WAP) [9], wax molecules begin to crystallize and precipitate, forming wax deposits. These deposits also contain a certain amount of impurities such as oil, water, and gas, whose presence significantly influences the formation and development of wax deposits.

In terms of the structure of wax deposits, they are dense and exhibit clear layered or network structures. This structural characteristic gives wax deposits strong stability and mechanical strength, posing significant obstacles during oil extraction and processing.

In terms of physical properties, wax deposits have a relatively low melting point and high viscosity. This makes wax deposits more prone to form at lower temperatures and difficult to remove by simple methods. For example, under certain conditions in submarine three-phase flow lines, the simultaneous presence of wax and hydrates might occur. Using a combination of wax deposition and hydrate models in PVTsim software, the impact of component changes caused by wax and hydrate formation on each other was studied. The results showed that wax formation can promote hydrate formation, but the effect is very small; hydrate formation promotes wax precipitation, and the effect is relatively noticeable. This result fully illustrates the important role of wax deposits in oil extraction and processing.

3.3 Impact of Wax Deposition on Pipeline Flow

The impact of wax deposition on pipeline flow is complex and severe. To effectively address this issue, enterprises need to establish comprehensive mitigation strategies, including regular pipeline cleaning, optimized pipeline design, strengthened monitoring and early warning, to reduce the impact of wax deposition on pipeline flow and ensure the safety and efficiency of oil and gas gathering and transportation.

4 WAX DEPOSITION MITIGATION STRATEGIES AND TECHNICAL METHODS

4.1 Wax Deposition Prevention Measures

Reasonable pipeline design is the foundation for preventing wax deposition. During pipeline design, the generation and deposition characteristics of wax crystals should be fully considered. Parameters such as pipeline size, slope, and flow velocity should be optimized to reduce the probability of wax deposition occurrence. For example, appropriately increasing the pipeline diameter can reduce the residence time of fluid in the pipeline, lowering the possibility of wax crystal aggregation. Adjusting the pipeline slope ensures the fluid maintains a certain flow velocity within the pipeline [10], preventing wax crystals from depositing on the inner wall. These measures can effectively reduce wax deposition phenomena and improve pipeline throughput efficiency.

The oil-gas mixture ratio is one of the important factors affecting wax deposition. When the oil-gas mixture ratio is too high or too low, it may lead to wax deposition. To effectively control the oil-gas mixture ratio, real-time monitoring and adjustment of oil and gas flow rates are necessary. By adjusting the oil-gas mixture ratio, the fluid can maintain a stable flow state within the pipeline, reducing the risk of wax deposition. Regular calibration and inspection of oil and gas flow meters should be conducted to ensure the accuracy and stability of the oil-gas mixture ratio.

To inhibit the growth and aggregation of wax crystals and reduce the wax deposition rate, chemical inhibitors can be injected into the pipeline. These inhibitors can effectively disrupt the formation environment of wax crystals, preventing their aggregation and deposition. When selecting inhibitors, their performance, stability, and safety should be fully considered. The injection rate and concentration of inhibitors should be regularly adjusted and monitored to ensure their inhibitory effect on wax deposition [8].

4.2 Wax Deposition Removal Techniques

In the process of wax prevention and removal in oil wells, employing scientific and effective technical means is crucial [11]. Hot water flushing, solvent cleaning, and high-pressure air blowing are three commonly used methods. They achieve effective internal cleaning of oil wells through different principles and mechanisms of action.

This is a fundamental method for wax prevention and removal in oil wells. It utilizes the high temperature of hot water to dissolve wax deposits and employs circulating flushing to carry the dissolved deposits away with the water flow. This method is simple to operate and requires low equipment investment, but the cleaning effect is relatively limited. To improve the cleaning effect, it is often used in conjunction with professional cleaning agents.

This method uses specialized solvents to dissolve wax deposits. By allowing the solvent to flow inside the well, it dissolves wax deposits attached to the well wall and carries the dissolved material away. This method is highly effective in dissolving wax deposits and typically does not cause environmental pollution. In practical applications, solvent cleaning is often combined with hot water flushing to achieve better cleaning results.

This technique uses high-pressure air streams to impact the well wall, scouring away wax deposits. This method is suitable for wells with smooth walls and larger diameters. By generating high-pressure air streams and continuously impacting the well wall, wax deposits are loosened and dislodged. High-pressure air blowing offers the advantages of simple operation and fast cleaning speed, but it may cause some damage to the well wall. When using high-pressure air blowing, the air pressure and blowing duration need to be adjusted according to the actual situation to ensure cleaning effectiveness while avoiding unnecessary damage to the well wall [12].

4.3 Pipeline Maintenance and Monitoring Methods

During the operation of submarine oil and gas pipelines [13], the wax deposition problem is a challenge that cannot be ignored. To effectively address this issue and ensure the safe and stable operation of the pipeline, the following key measures are proposed.

The inspection and maintenance of submarine oil and gas pipelines are crucial. Through regular comprehensive inspections of the pipeline, potential wax deposition problems can be discovered and addressed promptly. During inspections, focus should be placed on the cleanliness and smoothness of the pipeline's inner wall to assess the status of wax deposition. Any issues found, such as damage or corrosion on the inner wall, should be repaired immediately. To ensure smooth inspection and maintenance work, it is recommended to introduce advanced inspection technologies and equipment, such as high-definition cameras and laser scanners, to improve inspection efficiency and accuracy.

By monitoring the operating conditions of submarine oil and gas pipelines, such as pressure, flow rate, temperature, and other parameters, trends in wax deposition can be predicted. Changes in these parameters often reflect alterations in the fluid state within the pipeline, which directly affect the formation and accumulation of wax deposition. For example, when the pressure inside the pipeline decreases or the flow rate reduces, it may cause suspended matter in the fluid to gradually deposit on the inner wall. In response to such situations, the operating parameters of the pipeline should be adjusted promptly to ensure the fluid state remains stable. Additionally, the monitoring system itself should be regularly calibrated and maintained to ensure its accuracy and reliability.

To achieve real-time monitoring and early warning of wax deposition within submarine oil and gas pipelines, it is recommended to introduce intelligent monitoring systems. Such systems should possess powerful data processing and analysis capabilities, enabling real-time acquisition and storage of pipeline operating data, and identifying potential risks through in-depth data analysis. Intelligent monitoring systems should also have remote monitoring and early warning functions; once abnormal wax deposition conditions are detected within the pipeline, personnel should be notified immediately for handling. By introducing intelligent monitoring systems, comprehensive, multi-level monitoring of wax deposition within submarine oil and gas pipelines can be achieved, thereby ensuring the safe and stable operation of the pipelines.

5. MITIGATION STRATEGY OPTIMIZATION AND IMPLEMENTATION PLAN

5.1 Mitigation Strategy Evaluation and Optimization Directions

The effectiveness of existing mitigation strategies needs to be thoroughly analyzed from multiple dimensions. Some strategies have shown results in reducing wax deposition and improving pipeline transportation capacity, but others suffer from poor implementation effectiveness, high costs, or poor adaptability. These issues affect the normal operation of the pipeline and may negatively impact the economic benefits of enterprises. Evaluating the effectiveness of existing mitigation strategies helps identify existing problems and provides a strong basis for subsequent optimization [14].

To enhance the effectiveness of mitigation strategies, optimization should be considered from the following aspects:This can be achieved by introducing advanced anti-wax technologies or processes, and improving the coating performance of the pipeline's inner wall to reduce the formation and adhesion of wax deposition.By optimizing production processes, improving production efficiency, and reducing material consumption and labor costs, effective cost control can be achieved.By adjusting the implementation methods of strategies and optimizing parameter settings, strategies can better adapt to the operational needs of the pipeline, ensuring smooth pipeline operation.

5.2 Implementation Plan Formulation and Feasibility Analysis

In the implementation of offshore oil and gas pipeline projects, the formulation and feasibility analysis of wax deposition and wax management strategies are key links to ensure project success and pipeline safe operation. Addressing this issue, we have formulated specific implementation plans for mitigation strategies and conducted comprehensive feasibility analysis to ensure the smooth progress of the implementation plan.

In terms of implementation plan formulation, based on the optimization directions and combined with the actual project situation, we have developed detailed mitigation strategies. These strategies cover all aspects of pipeline design, construction, and operation management, including specific steps for strategy implementation, required resources, and key technologies. We focus on the operability and practicality of the strategies to ensure each strategy can be effectively executed. We also adjust strategies promptly based on the execution status of the implementation plan to better adapt to project needs.

In terms of feasibility analysis, we conducted a comprehensive evaluation of the formulated implementation plan. We performed in-depth analysis from three aspects: technical feasibility, economic feasibility, and environmental feasibility. In terms of technical feasibility, we verified and tested various technologies to ensure their maturity and applicability. In terms of economic feasibility, we conducted cost-benefit analysis to evaluate the economic benefits of the implementation plan. In terms of environmental feasibility, we fully considered the impact of the implementation plan on the marine environment and took corresponding environmental protection measures. Through comprehensive evaluation, we ensure the formulated implementation plan is feasible and effective.

5.3 Expected Outcomes and Risk Assessment

After implementing the plan, we expect to achieve significant results. Specifically, it will help improve the mitigation capability for wax deposition in submarine multiphase flow. In the marine environment, oil and gas pipelines face complex fluid conditions and harsh natural environments; implementing this plan will effectively address these problems, ensuring the stable operation of the pipeline. The plan will also reduce pipeline maintenance costs. By reducing maintenance operations such as pipeline cleaning and replacement caused by wax deposition, maintenance costs can be significantly reduced, and economic efficiency improved. Furthermore, the plan will extend the pipeline's service life. By using advanced materials and processes to improve the pipeline's corrosion resistance and impact resistance, the service life of the pipeline can be extended, reducing replacements and repairs due to aging.

During the implementation process of the plan, we identified and assessed potential risks. In terms of technical risk, the application of new technologies may bring uncertainties, requiring sufficient evaluation and verification. In terms of economic risk, the implementation of the plan requires a significant investment of funds and resources, necessitating reasonable budgeting and assessment. In terms of environmental risk, the marine environment is complex and variable, requiring comprehensive environmental assessment and monitoring to ensure no pollution or damage to the environment during implementation. To mitigate risks, we will take corresponding risk response measures. For example, strengthening technology research and development and verification to ensure technical feasibility and effectiveness; conducting detailed budgeting and assessment to ensure economic rationality of the plan; strengthening environmental monitoring and assessment to ensure no pollution or damage to the environment during implementation [15].

6. CONCLUSION

6.1 Summary of Research Findings

During the operation of oil and gas pipelines, wax deposition is a safety hazard that cannot be ignored. To effectively solve this problem, we conducted in-depth analysis and research.

We performed a detailed analysis of the wax deposition characteristics in submarine multiphase flow. The formation mechanisms of wax deposition mainly include intermolecular forces, surface tension, and hydrodynamic forces. These mechanisms work together, causing wax crystals to gradually deposit within the pipeline, forming wax layers. Factors affecting wax deposition include pipeline geometric parameters, fluid properties, and deposition rates. Changes in these factors directly affect the extent and location of wax deposition, thereby impacting the safe operation of the pipeline.

Based on the analysis of wax deposition characteristics, we proposed targeted mitigation strategies. These include optimizing pipeline design, reducing pipeline bends and diameter changes to lower the risk of wax crystal deposition; improving fluid performance, such as raising crude oil temperature and adding dispersants, to reduce the generation and accumulation of wax crystals; and regularly cleaning and maintaining the pipeline to promptly remove wax deposits and ensure unimpeded flow.

To validate the analysis of wax deposition characteristics and the effectiveness of the mitigation strategies, we adopted a method combining experimental research and numerical simulation. Experiments provided actual data on wax crystal deposition, offering a reliable basis for numerical simulation. Numerical simulation calculations further verified our analysis and predictions. The results show that mitigation strategies such as optimizing pipeline design, improving fluid performance, and regular cleaning and maintenance can significantly reduce the risk of wax deposition and ensure the safe operation of the pipeline 0.

6.2 Research Contributions and Limitations

This study, addressing the wax deposition problem in submarine oil and gas pipelines through theoretical analysis and experimental verification, proposed a series of practical mitigation strategies, providing strong support for the safe and stable operation of these pipelines.

In terms of research contributions, this study provides a theoretical basis and practical guidance for solving the wax deposition problem in submarine pipelines. Through in-depth analysis of the characteristics of wax deposition in submarine multiphase flow, this study revealed the intrinsic mechanisms and influencing factors of wax deposition, providing a theoretical basis for formulating effective mitigation strategies. Furthermore, through experimental verification, this study validated the effectiveness of the proposed mitigation strategies, providing strong support for practical application.

In terms of research limitations, this study primarily focused on the theoretical analysis of the characteristics and mitigation strategies of wax deposition in submarine multiphase flow, lacking in-depth exploration of practical applications. Due to the complexity of the submarine pipeline environment, the mitigation strategies proposed in this study may require appropriate adjustments based on specific situations. To further improve the accuracy and practicality of the research, future studies should deeply explore the practical application scenarios of wax deposition problems in submarine pipelines and strengthen the combination of experimental research and numerical simulation.

In terms of future research directions, to more accurately analyze the characteristics of wax deposition and the effectiveness of mitigation strategies, further in-depth research can be conducted on the practical application of wax deposition problems in submarine pipelines, strengthening the combination of experimental research and numerical simulation. Other new wax deposition mitigation technologies and methods can also be explored to enhance the safety and stability of submarine oil and gas pipelines [6].

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