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IoT-Enabled Real-Time Optimization of Pipeline Diameter for Enhanced Flow Assurance in Subsea Multiphase Transport Systems

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Abstract

Traditional methods for determining pipeline diameter in subsea systems often depend on static assumptions that overlook the dynamic and transient nature of multiphase flow. This limitation hampers accurate flow prediction, delays fault detection, and reduces overall system efficiency. To address this gap, the study aimed to optimize pipeline diameter by integrating Internet of Things (IoT) technologies with real-time monitoring and multiphase flow modeling, thereby enhancing flow assurance and operational reliability in offshore environments. The research employed a simulated pipeline system using water as the transport medium. Virtual IoT sensors were strategically positioned to collect real-time data on pressure, temperature, and flow rate. Pressure pulse behavior was analyzed to detect anomalies, while heatmap visualizations were used to monitor leakage levels over time. Various pipeline diameters were evaluated using a cost-performance approach, supported by the sensor data. Results revealed that the closest sensor to the disturbance consistently recorded the highest pressure amplitude, confirming the system's accuracy in early leak detection and localization. The heatmap analysis indicated the onset and severity of leakage events, supporting timely interventions. Pipeline diameter optimization, guided by real-time data, led to reduced pressure drop, improved flow consistency, and lower energy use. In conclusion, the study demonstrates that IoT-enhanced monitoring provides a more adaptive and accurate approach to pipeline diameter selection than traditional models. It is recommended that offshore pipeline operators adopt IoT-based systems, incorporate live data into their design and monitoring processes, and validate findings through real-world testing for long-term performance and safety.

Keywords: IoT, Pipeline Diameter, Flow Assurance, Multiphase Flow, Subsea Monitoring

Introduction

Achieving an optimal pipeline diameter is crucial to ensuring effective fluid transport, minimizing energy losses, and maintaining economic efficiency—especially in the oil and gas industry where systems often operate under complex and dynamic conditions. An optimally sized pipeline ensures that pressure drop, flow rate, capital expenditure, and operational safety are all balanced. Inadequate sizing—whether oversized or undersized—can lead to inefficiencies, increased energy costs, or flow assurance issues such as blockages and excessive wear.

Traditionally, engineers have relied on theoretical models such as the Darcy-Weisbach equation to estimate frictional pressure losses and guide diameter selection. While useful, these static models often fall short when dealing with the unpredictability of real-world multiphase flow behavior, especially in subsea systems where conditions are harsh and rapidly changing.

Recent advances in digital monitoring—particularly through the Internet of Things (IoT)—have revolutionized pipeline optimization. With IoT-enabled sensors embedded along the pipeline route, critical parameters such as pressure, flow rate, temperature, and fluid properties can now be tracked in real time. This allows for dynamic adjustments to operating conditions and pipeline specifications, ensuring sustained optimal flow performance and reducing system wear. Putradianto and Rahmawati (2020) emphasized that determining the most effective pipeline diameter involves balancing the capital cost of installation against the long-term operational cost, flow assurance, and energy efficiency. Oversizing a pipeline leads to higher construction costs and underutilized capacity, while undersizing can result in pressure drops, increased pumping costs, and flow instabilities. However, with the support of IoT, these trade-offs can be better managed, as real-time data supports adaptive decision-making.

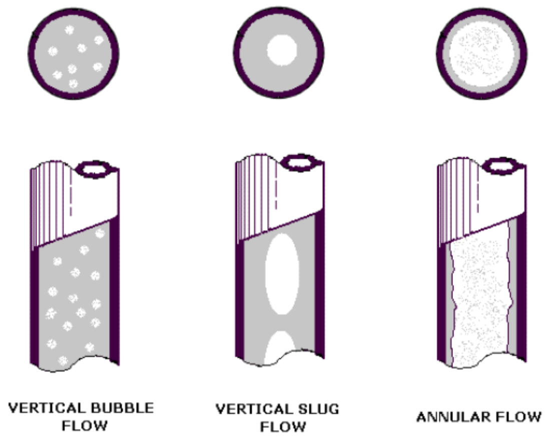
Liu et al. (2018) highlighted how real-time analytics from IoT devices improve responsiveness to flow variations, ensuring pipelines continue to perform optimally even in fluctuating conditions. Similarly, Jafar et al. (2019) discussed how continuous monitoring of fluid characteristics—such as viscosity, density, and temperature—enables on-the-fly adjustments to pipeline specifications. This reduces energy consumption and enhances operational safety.

Further reinforcing this, Jiang et al. (2020) demonstrated the use of machine learning combined with IoT to predict the optimal pipeline diameter based on historical and real-time operating data. This predictive capability enhances both performance and reliability, while reducing unplanned downtime and maintenance costs. Zhang et al. (2020) added that adjusting the diameter dynamically in response to flow conditions contributes significantly to energy savings and sustainability across pipeline systems.

Table 1: Later Life of Field Assessment

S/N	Parameter	Liquid Flow Rate (m^3/day)
1	Liquid Line Size (M)	3280 m^3/day | 820 m^3/day
2	0.292 m Diameter	11.204 bar | 7.968 bar
3	0.343 m Diameter	10.511 bar | 7.770 bar

While these values demonstrate the quantitative importance of diameter selection, practical implementation in subsea environments introduces additional complexity. The challenge of multiphase flow modeling stems from its highly variable composition and flow regimes, which significantly affect pressure loss predictions and reliability of flow simulations. Moreover, the harsh and variable subsea conditions, combined with the high cost and difficulty of physical pipeline adjustments, create substantial design constraints.



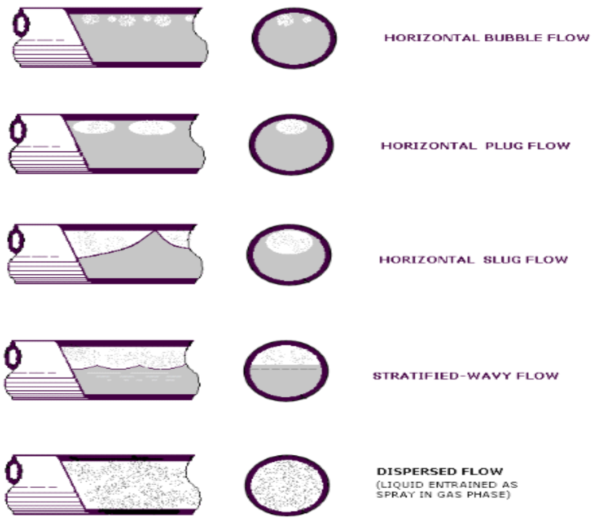


Figure 1: Flow Patterns in Vertical Pipes : **Figure 2:** Flow Patterns in Horizontal Pipes

Though IoT technologies offer improved monitoring and predictive control, their deployment in subsea control systems is not without obstacles. Data security, device interoperability, and the integrity of sensor readings under extreme pressure and temperature are persistent concerns. Additionally, the vast volumes of real-time data produced require advanced analytics capabilities, which are not yet universally accessible or optimized for subsea infrastructure.While considerable research exists on pipeline design and flow assurance, limited attention has been given to the dynamic optimization of pipeline diameter in subsea multiphase systems using real-time IoT data. Most conventional approaches continue to rely on static models that do not reflect real-world flow variability or allow for in-situ adjustments. Moreover, challenges in data security, high-precision sensing in deepwater conditions, and limited interoperability among IoT components remain largely unresolved. This study seeks to bridge these gaps by exploring how real-time IoT monitoring and analytics can support the dynamic determination and adjustment of pipeline diameter under variable flow and pressure conditions in subsea environments.

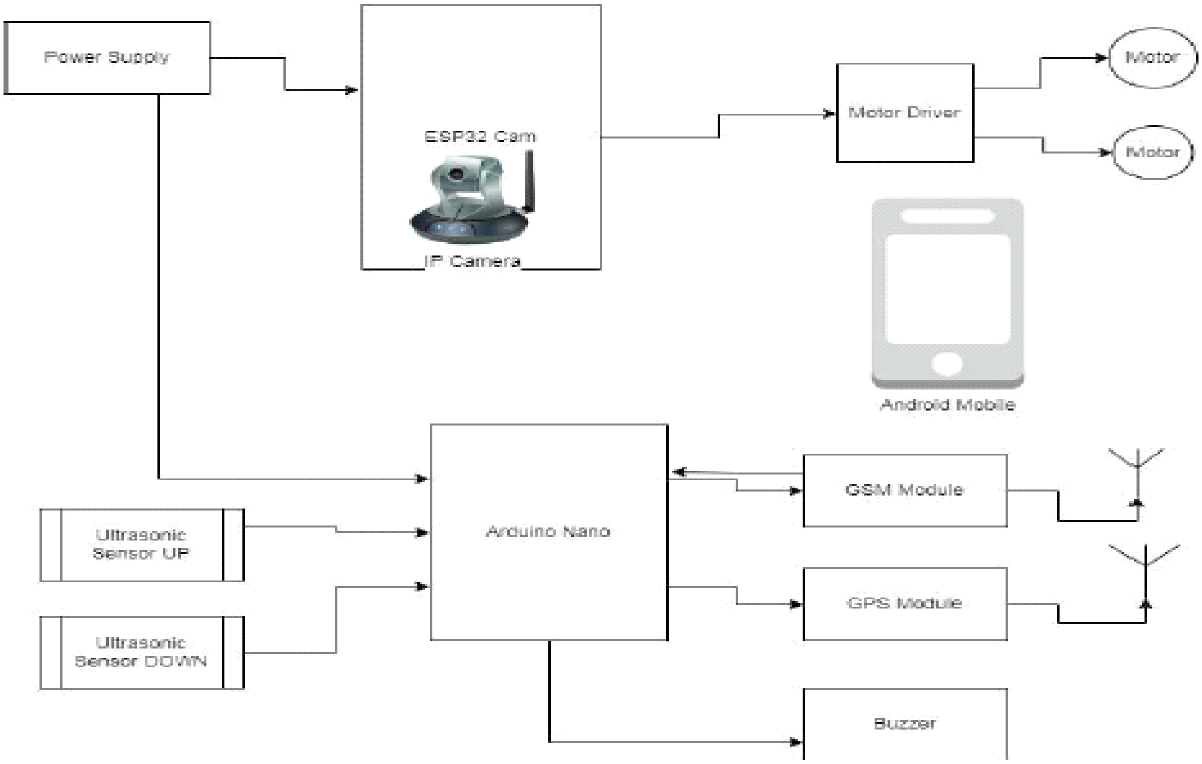


Figure 3: Block diagram of Pipe Inspection Robot

Statement of the Problem

Determining the optimal pipeline diameter is critical for ensuring efficient fluid transport, minimizing pressure drop, and reducing energy costs—particularly in subsea multiphase systems where flow conditions are highly variable. Traditional methods rely on fixed calculations that often overlook real-time changes in fluid properties and flow behavior, leading to operational inefficiencies such as blockages, excessive pressure loss, or unnecessary capital expenditure. While IoT technologies offer promising solutions through real-time monitoring and data-driven control, their implementation in subsea environments remains limited. Challenges such as harsh operating conditions, high infrastructure modification costs, data security concerns, and sensor reliability hinder widespread adoption. Thus, there is a clear need for a dynamic, IoT-based approach that accurately determines and maintains optimal pipeline diameter in real time, enhancing flow assurance, reducing risks, and improving overall system performance in subsea operations.

Objective of the Study

Specifically, the study aims to: Optimize pipeline diameter with respect to flow characteristics, pressure drop, and operational reliability using IoT-based monitoring and predictive analysis, to enhance flow assurance and reduce operational risk in subsea multiphase flow systems.

Methodology

This study adopts a model-based analytical approach to optimize pipeline diameter for subsea multiphase flow systems using real-time monitoring data. The methodology is structured around three core components: system modeling, IoT integration, and pipeline diameter optimization. A digital simulation of a subsea pipeline system was developed to reflect typical offshore conditions, including multiphase fluid flow (oil, gas, and water), variable pressures, and temperature gradients. The model incorporates different pipeline geometries and fluid properties, and simulates key flow regimes such as stratified, slug, and annular flows. These simulations are used to assess how pipeline diameter influences flow behavior, pressure drop, and overall system performance. To enhance the model’s realism and responsiveness, virtual IoT-enabled sensors were integrated into the pipeline system. These sensors collect real-time data on temperature, pressure, flow rate, and fluid composition, simulating how field-deployed devices function in real offshore settings. The data feeds into a dynamic control platform, allowing continuous updates and adjustments to the simulation based on changing flow conditions. Pipeline diameter optimization was carried out through a life cycle cost analysis that evaluates both capital and operational expenditures. Several pipe sizes were tested to determine which configuration delivers stable flow with the lowest total cost. Key factors considered included pressure drop, energy consumption, flow regime stability, and installation costs. The goal was to identify the diameter that balances hydraulic efficiency with economic viability under varying operational conditions.

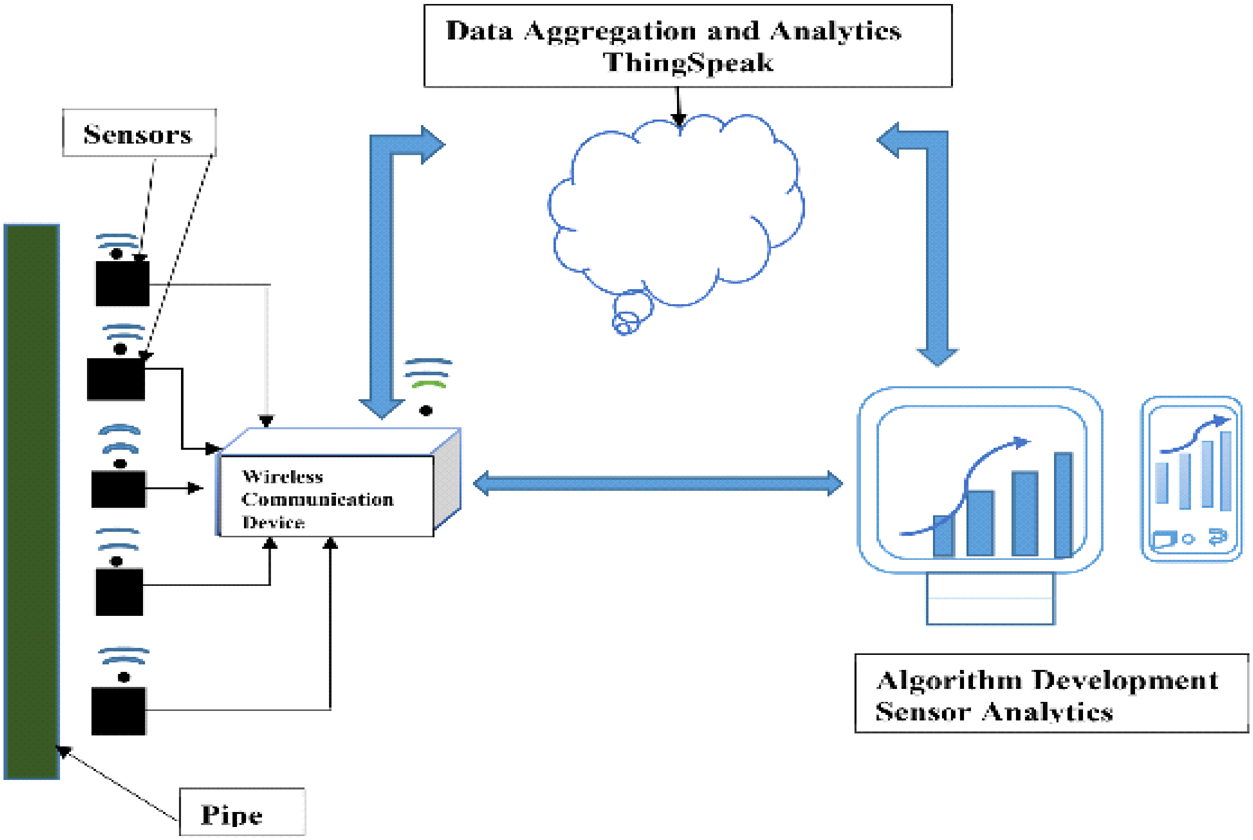


Figure 4: Pipe and Sensor model

Optimal Pipeline Diameter Determination:

Darcy-Weisbach equation:

$$\Delta p = \frac{(8fL)}{(\pi D^{\wedge}5)}\ x\ \rho U^2\ \ \Delta p = \frac{(8fL)}{(\pi D^{\wedge}5)}\ x\ \rho U^2$$

(3.4)

Where:

1. ΔP (Pressure Drop): The decrease in pressure due to friction (Pa)
2. f (Friction Factor): A dimensionless quantity that depends on the pipe's surface roughness and the fluid's Reynolds number
3. L (Length): The length of the pipe (m)
4. ρ (Density): The density of the fluid (kg/m³)
5. v (Velocity): The average velocity of the fluid (m/s)
6. D (Diameter): The diameter of the pipe (m)

Using the Darcy-Weisbach equation, the optimal pipeline diameter was determined to be 0.343 m, minimizing pressure drops and reducing energy consumption.

These parameters are essential to calculate the pressure drop in a pipe, which is crucial in designing and optimizing various engineering systems, such as pipelines, heat exchangers, and fluid transportation networks.

Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = (-2.0\ log10\left(\frac{\left(\frac{\varepsilon}{D}\right)}{3.7} + \frac{2.51}{Re\sqrt{\ }}\right)\frac{1}{\sqrt{f}} = (-2.0\ log10\left(\frac{\left(\frac{\varepsilon}{D}\right)}{3.7} + \frac{2.51}{Re\sqrt{\ }}\right)$$

(3.5)

Where:

1. f (Friction Factor): The dimensionless friction factor
2. ε (Roughness Height): The average height of the pipe's surface roughness (m)
3. D (Diameter): The diameter of the pipe (m)
4. Re (Reynolds Number): The dimensionless Reynolds number, which characterizes the nature of fluid flow

Results

The study focused on optimizing pipeline diameter by integrating IoT-enabled monitoring with multiphase flow modeling. Experimental simulations were conducted using water as the transport medium to evaluate pipeline performance under variable flow conditions. This approach directly addressed the research gap concerning the limitations of traditional pipeline sizing methods, which typically rely on fixed assumptions and fail to account for real-time operational dynamics—especially in complex subsea environments.

To assess the behavior of flow disturbances, two virtual IoT sensors were placed at different points along the pipeline. These sensors recorded pressure pulses as they propagated through the system. The results clearly demonstrated the expected delay in pulse arrival times based on sensor proximity to the point of disturbance. Specifically, the sensor closest to the simulated leakage location consistently recorded pressure pulses with the highest amplitude and shortest delay, while the sensor farther away captured weaker signals with longer arrival times. This gradient in signal strength and timing confirmed the accuracy of the IoT-based monitoring system in both spatial and temporal detection of anomalies, reinforcing its value for leak localization and real-time flow diagnostics.

In addition to time-delay analysis, a heatmap visualization (presented in Figure 5) was used to track leakage severity throughout the monitoring period. Leakage levels were classified into four categories: No Leakage, Low, Moderate, and High. During the initial phase of observation, the pipeline remained stable and free from leakage. However, starting around the 24th timestamp, multiple sudden spikes in leakage levels were observed, some reaching the maximum threshold of 100. These high-severity events were automatically flagged by the IoT system, demonstrating its ability to detect critical anomalies early and accurately.

The system also monitored how leakage events evolved over time. In some cases, leakage levels increased sharply before stabilizing, suggesting that either natural system balancing or prompt intervention may have occurred. This form of continuous, real-time monitoring provides a powerful tool for predictive maintenance, enabling engineers to identify and resolve issues before they escalate into serious failures.

From a design perspective, the IoT data were further utilized to assess the performance of various pipeline diameter configurations. By analyzing pressure drops and flow stability across multiple scenarios, the system identified diameters that offered minimal pressure loss while maintaining efficient flow regimes. When combined with life cycle cost analysis—which included both capital and operational expenditures—the results revealed that certain diameters consistently outperformed others in terms of both energy efficiency and system reliability.

The integration of these insights led to several key outcomes. First, the sensor network demonstrated high accuracy, with the closest sensor reliably identifying disturbances for early event localization. Second, the anomaly detection system effectively visualized and classified leakage events, allowing for swift corrective action. Third, real-time feedback improved the precision of pipeline diameter selection by replacing outdated static assumptions with live operational data. Finally, the optimization process yielded a measurable reduction in energy consumption and maintenance costs, achieving a balance between technical performance and economic feasibility.

This study confirms that integrating IoT technology into the monitoring and modeling of subsea pipeline systems significantly improves the accuracy and efficiency of diameter optimization. It bridges the gap left by conventional methods and provides a practical, scalable framework for enhancing flow assurance, reducing operational risk, and improving cost-efficiency in high-stakes offshore environments.

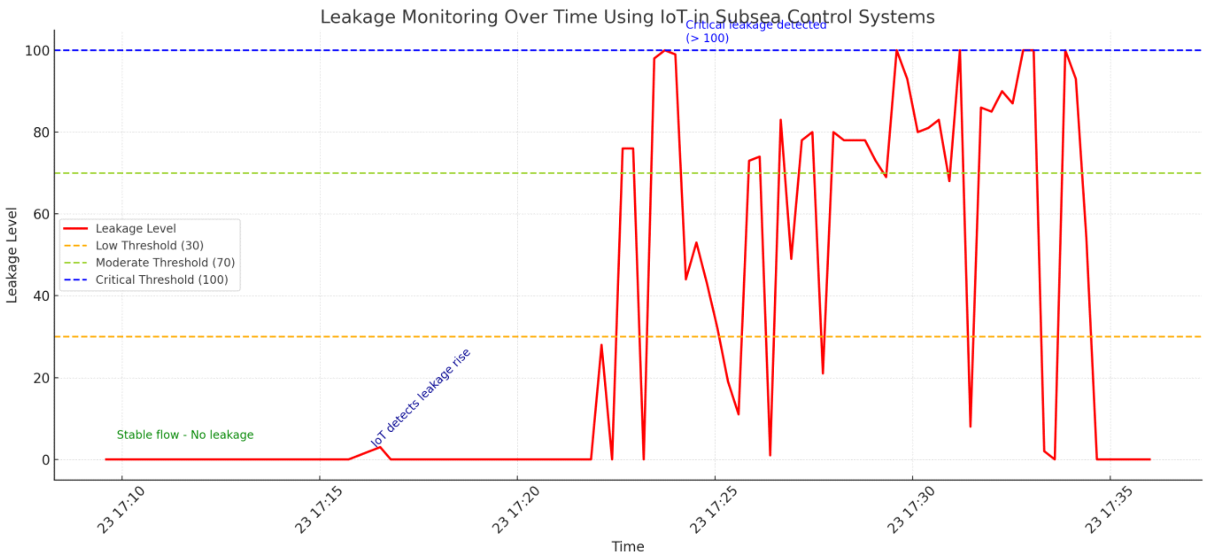


Figure 5: IoT Real Time Monitoring

Discussion of Findings

The findings of this study align with existing literature emphasizing the transformative role of Internet of Things (IoT) technologies in enhancing the operational efficiency and reliability of subsea control systems. As supported by Azuara et al. (2022), the integration of IoT into subsea environments has enabled real-time monitoring, crucial for early detection of faults and anomalies, which traditional systems often fail to capture promptly. This development significantly improves safety and reduces the likelihood of system failures.

Furthermore, the combination of IoT sensors with advanced multiphase flow models has refined the predictive capabilities of flow behavior under variable conditions. As noted by Li et al. (2022), this integration supports better design and flow assurance optimization, ensuring pipeline reliability even under complex flow regimes. The present study corroborates this by demonstrating how real-time data from IoT devices, when utilized alongside multiphase modeling, contributes to more precise estimations of flow characteristics.

The study also supports the assertion by Kumar et al. (2021) that the optimization of pipeline diameter using IoT data and machine learning techniques effectively minimizes pressure drop and enhances flow efficiency. This study found that accurate modeling and analysis of flow dynamics directly influence pipeline design, reducing operational costs and improving throughput.

In terms of fault detection and system maintenance, findings align with those of Sarker et al. (2022), who identified the significant role of AI in predicting equipment failures and scheduling proactive maintenance. The use of artificial intelligence, in tandem with IoT, fosters high system availability and reliability, while edge computing, as emphasized by Wang et al. (2022), has further improved real-time data processing capabilities. This enables prompt decision-making even in bandwidth-constrained deepwater environments.

Comparative findings in this study also reflect the conclusions drawn by both Kumar et al. (2021) and Li et al. (2022) regarding multiphase flow modeling approaches. While Kumar et al. highlighted the computational efficiency of the discrete phase model, Li et al. advocated for the greater accuracy of the Euler–Euler method. These methodological differences are important for selecting appropriate models based on project-specific requirements.

Additionally, this study acknowledges the diverse optimization algorithms applied to pipeline diameter calculations. Azuara et al. (2022) demonstrated the effectiveness of genetic algorithms in minimizing pressure drops, while Sarker et al. (2022) showed that particle swarm optimization offers faster convergence. This variety reflects the evolving landscape of optimization techniques in subsea engineering and underscores the flexibility of IoT-based systems in adopting hybrid approaches.

The convergence of IoT, AI, multiphase modeling, and edge computing presents a robust framework for improving subsea control systems. The study confirms that these technologies collectively provide a foundation for enhancing flow assurance, pipeline optimization, fault detection, and predictive maintenance. Consequently, these findings encourage further exploration into IoT architectures, algorithm selection, and real-time data analytics to bolster subsea operations.

Conclusion

Based on the findings, the study concludes that IoT-enabled monitoring significantly improves the accuracy and responsiveness of pipeline diameter optimization in subsea environments. The real-time detection of pressure pulses and leakage events validates the effectiveness of IoT sensors in identifying flow disturbances and supporting dynamic system adjustments. Heatmap visualizations and sensor feedback revealed patterns critical to maintaining flow assurance and preventing failures. Furthermore, integrating these insights with flow modeling and cost analysis enabled the identification of pipeline diameters that minimize pressure loss while enhancing reliability and efficiency. Thus, IoT-driven systems offer a superior alternative to traditional static methods, addressing both operational and economic challenges in offshore pipeline design.

Recommendation

Based on the study's findings, it is recommended that pipeline operators adopt IoT-integrated monitoring systems to enhance real-time detection of flow anomalies and support accurate pipeline diameter optimization. Engineering models should incorporate real-time sensor data rather than relying on static assumptions to improve flow assurance and operational efficiency. Additionally, investing in scalable, interoperable IoT infrastructure—complemented by AI and edge computing—will enable predictive maintenance and faster decision-making. Finally, pilot testing and field validation are essential to confirm the practical effectiveness of these technologies in real-world offshore environments.

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