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IoT-Based Continuity Analysis of Oil Pipeline Leakages

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Abstract

Oil pipeline leaks pose a serious challenge due to their potential to cause significant economic losses and severe environmental damage. These incidents can disrupt industrial operations and endanger nearby ecosystems and communities. Early detection and real-time monitoring are therefore essential for minimizing adverse impacts and enabling rapid response. This research develops an Internet of Things (IoT)-based oil pipeline leak monitoring system using integrated multi-sensor data collected from field-simulated scenarios, providing a realistic evaluation of system performance under near-operational conditions. The system incorporates an ultrasonic sensor (HC-SR04) to measure fluid levels, a temperature sensor (DS18B20) to detect thermal anomalies, and a pressure sensor to identify internal pressure fluctuations. Sensor data are wirelessly transmitted via a NodeMCU ESP32 microcontroller to a web-based dashboard for remote monitoring, while local readings are simultaneously displayed on an LCD screen for on-site observation. The system was evaluated through controlled experiments simulating variations in pressure, temperature, and induced leak conditions. Results showed that the system achieved over 95% accuracy in leak detection, with a response time of less than 60 seconds upon leak initiation. The flow rate deviations under leak conditions exceeded the ±3% detection threshold, triggering real-time alerts. In non-leak scenarios, flow rates remained steady between 1.5–2.1 L/min, with tank level variations within 1 cm, confirming strong mass balance and stability. Overall, the developed IoT-based monitoring platform demonstrated high reliability and effectiveness in real-time leak detection, enabling faster response and significantly reducing potential environmental and operational impacts.

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1. Introduction

Pipeline leaks are a critical concern for industries that operate fluid distribution systems. As pipeline networks continue to expand, the frequency of leak incidents has also increased, with many going undetected or unaddressed, posing substantial environmental and economic risks [1], [2]. These leaks often result in a significant drop in pressure within the system and typically occur due to structural damage, such as cracks or holes, allowing the uncontrolled release of liquids, gases, or solids from the pipeline [3].

Advancements in sensor technology and the Internet of Things (IoT) have significantly improved the ability to monitor pipeline networks. Water flow sensors, for instance, are employed to measure flow rates and the volume of fluid passing through pipelines—data that is essential for identifying anomalies indicative of leaks. Complementing this, IoT technology facilitates real-time data transmission from sensors to cloud-based systems, enabling advanced analytics for tracking flow rates, monitoring consumption patterns, and detecting sudden changes that suggest leakage [4].

Understanding the behavior of fluids in pipelines is fundamental to leak detection and prevention. Properties such as viscosity, flow velocity, and pressure strongly influence flow stability and are key indicators of leak occurrences. When a leak develops, these parameters shift—creating detectable anomalies in flow rate and pressure patterns [5]. Despite this, many industries still rely on manual field inspections for leak detection. These inspections are labor-intensive, time-consuming, and often ineffective for large or remote pipeline networks, leading to delays in response and mitigation [6].

To address this, early detection systems have become increasingly essential. The integration of big data analytics and predictive modeling enables more proactive leak detection by identifying statistical anomalies in historical sensor data. These systems can predict potential leaks before they occur, allowing for timely maintenance and reduced operational risk [7]. Unlike conventional methods, which require continuous field inspections prone to human error, IoT-based systems offer automatic alerts, real-time data logging, and high detection accuracy—making them particularly well-suited for large-scale infrastructures [8].

In developing countries such as Indonesia, pipeline leak detection remains a major challenge due to limited technological infrastructure. Many pipelines, particularly in the oil sector, were installed decades ago and lack modern monitoring systems. IoT-based detection offers a cost-effective and scalable solution that can be retrofitted into existing infrastructure and monitored remotely via internet connectivity [9]. The selection of components in such systems is based on the characteristics of the pipelines and the fluids being monitored. Ultrasonic sensors are preferred for non-contact fluid level measurement, while pressure sensors detect abrupt pressure drops indicative of leaks. The ESP32 microcontroller is selected for its built-in Wi-Fi capabilities and high processing performance, supporting real-time data transmission to web-based monitoring platforms. This configuration has proven effective in various pipeline monitoring studies [10], [11].

Miniaturized pipeline systems are useful for testing and validating leak detection approaches before full-scale deployment. To ensure accuracy, these models must replicate the dynamic behaviors of actual pipelines, such as viscosity, flow velocity, and pressure. However, scaling effects—including increased surface friction and turbulence—pose challenges in maintaining similarity. Accuracy depends on factors like material selection, sensor placement, and flow control mechanisms. For effective leak detection, miniaturized systems must simulate both steady and transient flow conditions to capture deviations caused by leaks. Proper sensor calibration is crucial for detecting subtle anomalies. The integration of IoT sensors enables real-time data analysis and comparison with predictive models, improving detection accuracy over time. High-precision components such as the ESP32 microcontroller have been shown to increase the effectiveness of miniaturized systems, with some studies reporting detection accuracies exceeding 95% in controlled laboratory settings, especially when combined with advanced data analytics and machine learning [12].

This research aims to develop an IoT-based pipeline leak detection system with real-time monitoring capabilities accessible through a web-based application. The proposed system eliminates the need for manual field inspections, enabling prompt identification of leak points and enhancing pipeline maintenance efficiency. By reducing delays in leak detection and response, the system minimizes both environmental and economic impacts. The IoT platform facilitates automatic data collection and communication between devices, enabling responsive, real-time decision-making in oil distribution systems [13], [14]. Beyond operational efficiency, the environmental implications of oil leaks are severe. Spilled oil can pollute rivers and marine ecosystems, cause mass mortality among aquatic life, and degrade groundwater quality—posing long-term threats to biodiversity and public health [15].

2. Methods

This research began with a comprehensive literature review on feasibility studies and planning processes to gain insights from prior research in the relevant field. The methodology is outlined as follows, with sufficient detail provided to ensure the reproducibility of the work. Where methods have been previously published, appropriate references are cited; only relevant modifications to these methods are described.

2.1. Pipeline configuration

Figure 1 illustrates the two-dimensional schematic of the T-shaped oil pipeline system. The design connects three tanks (Tank 1, Tank 2, and Tank 3) via a 45 cm main header and two 25 cm branch pipelines. Key components are indicated using color-coded symbols: orange blocks represent five YF-S201 flow sensors, pink blocks mark three HC-SR04 ultrasonic level sensors, red blocks denote three solenoid valves, and black circles highlight intentional leak points for simulation and testing purposes.

During the instrumentation and design phase, all flow and level sensors were systematically installed, tested, and calibrated to ensure the accurate acquisition of critical data. This process generated two essential data streams. The first stream consists of quantitative measurements, including real-time flow rates across each segment of the pipeline and fluid levels within the three storage tanks.

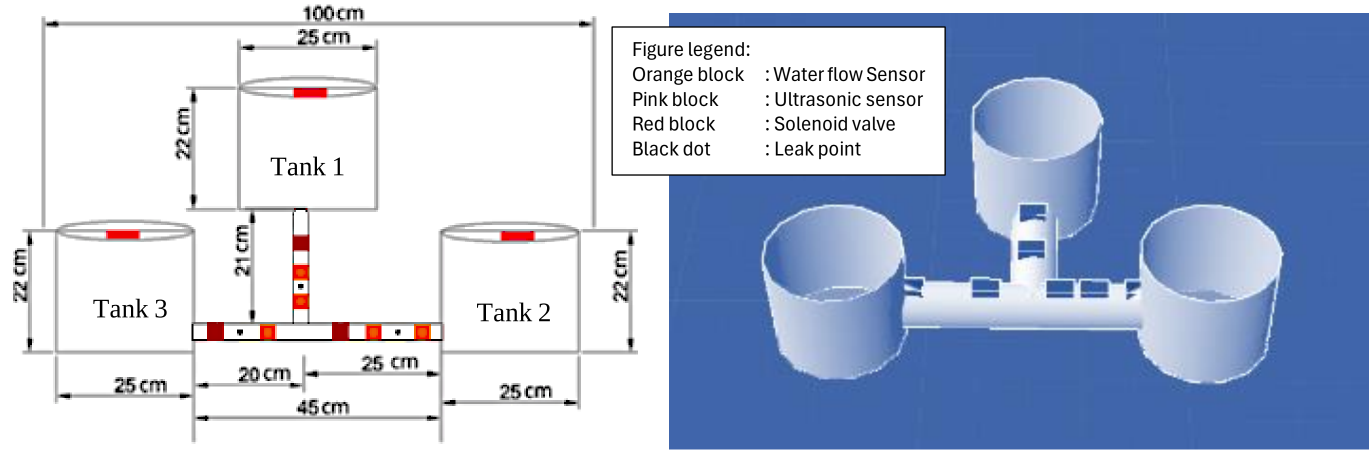


Figure 1. Schematic of the T-shaped oil pipeline system

The second stream provides diagnostic insights by identifying discrepancies between the volume of fluid transported through the pipelines and the corresponding changes in tank levels. Such discrepancies can signal potential anomalies, such as undetected leaks or sensor malfunctions.

These data streams serve as the foundation for several key functions in the system. They support the validation of the solenoid valves' automatic cutoff logic, ensuring timely shut-off in the event of abnormal flow conditions. They also enable the early detection of leaks at three designated critical points—specifically, the left branch, right branch, and central pipeline. Furthermore, the data provides an empirical basis for refining control algorithms, setting appropriate alarm thresholds, and developing effective loss-mitigation strategies under various operational scenarios.

The research implementation begins with an in-depth literature review of existing sensor technologies, leak detection techniques, and pipeline control strategies. The insights obtained from this review inform the selection of hardware components, system architecture, and experimental protocols applied during the instrumentation and design phase.

2.2. Sensors and control system

Figure 2 illustrates the design and operational components of the oil flow testing system, which is driven by a 12 V gear pump (orange label 1) with a rated flow capacity of 12 L/min, a maximum head of 2 meters, and a current draw of 1.8 A. The system is centrally controlled by an ESP32 microcontroller, which manages the coordination of sensor data acquisition and device control.

In operation, the gear pump draws oil from Tank 1 and delivers it through a series of solenoid valves (cyan labels 1–3). These valves distribute the flow into two branches, routing oil toward Tank 2 and Tank 3. Each pipeline branch is equipped with YF-S201 flow sensors (green labels 1–5), capable of measuring flow rates ranging from 1 to 30 L/min.

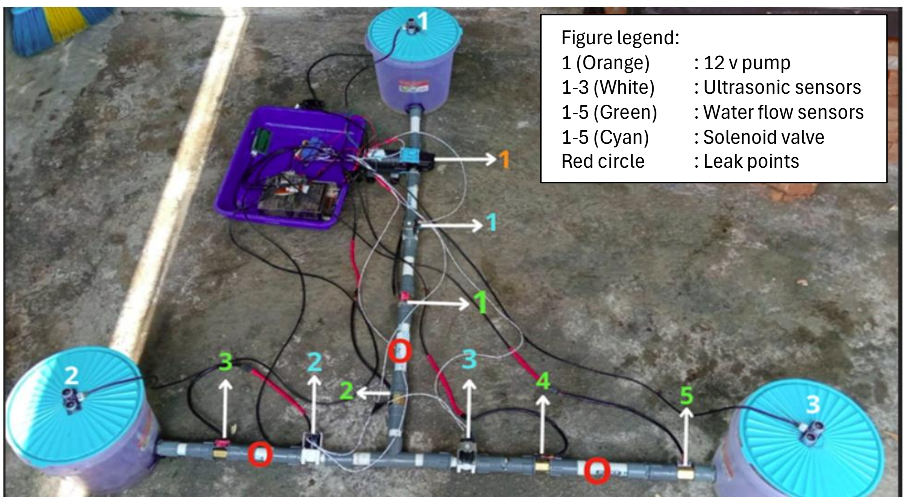


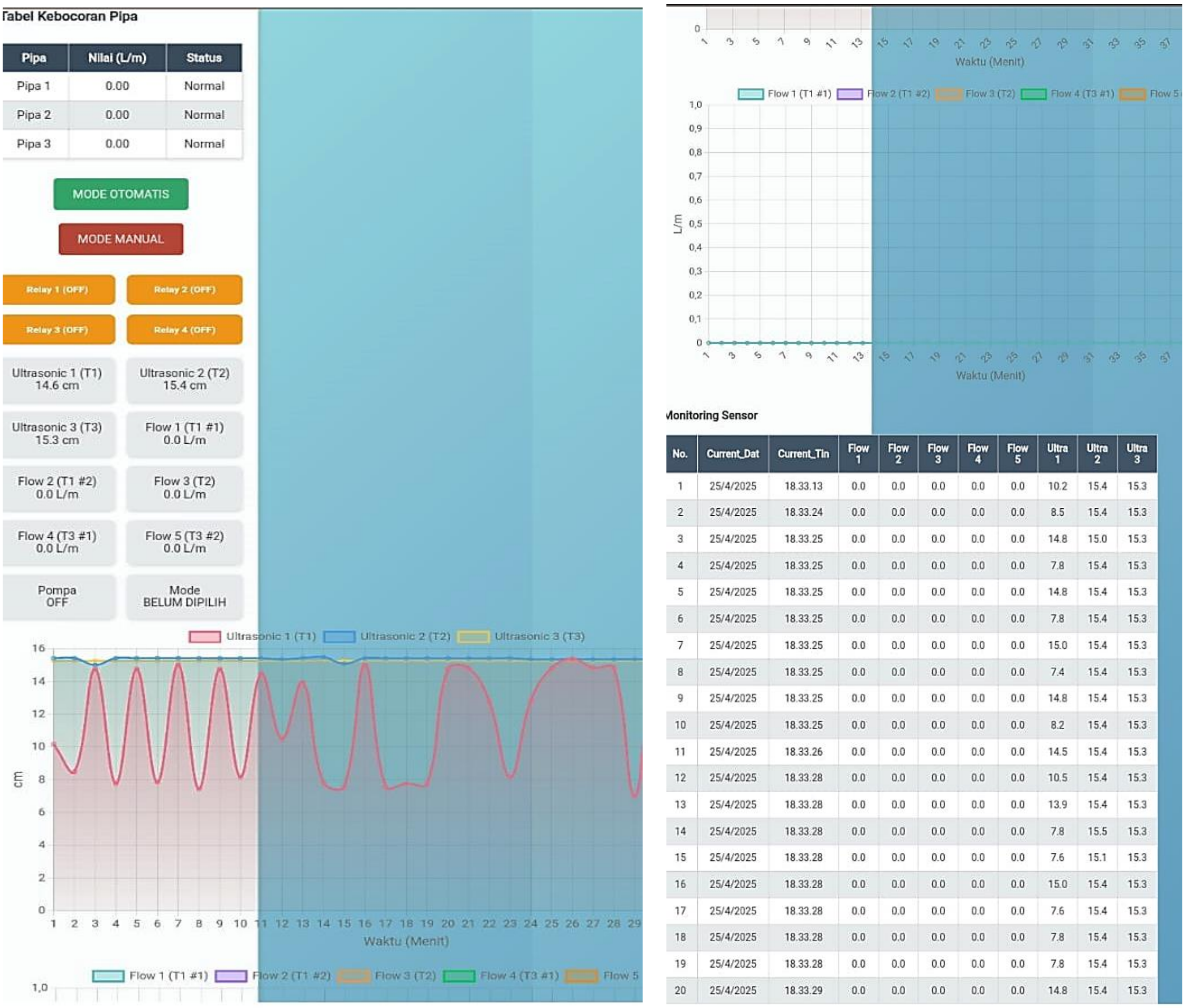
Figure 2. Components of oil-flow testing system

These sensors provide real-time volumetric flow data as the oil is circulated through the system. To monitor the liquid level in each tank, HC-SR04 ultrasonic sensors (white labels 1–3) are installed, with a range of 2–400 cm and a resolution of 3 mm. These sensors are used when the tank lids are open, allowing accurate tracking of the oil level changes during the testing process. Additionally, three red-circled points along the pipeline indicate designated leak locations, which are used for validation experiments aimed at testing the system's leak detection capabilities.

At the start of each test run, the ESP32 microcontroller activates the gear pump and sequentially opens the solenoid valves to establish the intended flow path. It then continuously collects data from all sensors—pulse counts from the flow sensors and echo times from the ultrasonic sensors. The system functions cohesively, with the pump providing the driving force for circulation, the solenoid valves directing the flow, and the sensors recording flow rates and tank levels. The ESP32 not only manages this process in real time but also logs the data for subsequent analysis. The entire assembly is powered by a regulated 12 V / 5 A power supply and is housed within a protective ABS enclosure to ensure electrical stability and safe operation during testing.

2.3. Pipeline monitoring system

Figure 3 presents the web-based pipeline leakage monitoring system, which integrates real-time sensor data acquisition with automated and manual control capabilities.



(a) (b)

Figure 3. Web-based pipeline leakage monitoring system; (a) Dashboard, (b) Detailed view

The system utilizes ultrasonic, and flow sensors strategically installed at various points within the pipeline to measure real-time flow rates and water levels. These measurements are processed and visualized through a user interface that enhances system monitoring and control.

The first interface image (Figure 3a) displays the real-time status of sensors on Pipes 1, 2, and 3. Ultrasonic sensor readings are shown in centimeters, along with operational status indicators such as "Normal." The system provides two modes of operation: Automatic Mode, in which control is algorithm-driven based on sensor data, and Manual Mode, allowing users to override system logic for direct control. The interface also features dynamic graphs that track variations in flow and water level measurements. Each sensor is color-coded within the graphs for ease of identification and monitoring. The second interface image (Figure 3b) offers a more detailed view of system performance. It includes graphs showing real-time data from the five flow sensors (Water Flow 1 to 5) and three ultrasonic sensors (Ultrasonic 1 to 3). These graphs help detect abnormal fluctuations that may signal a leak or other system anomalies. A corresponding data table records the date, time, and measured sensor values for historical analysis and traceability.

In terms of hardware integration, the system includes a pump controlled by Relay 1, which circulates water through the pipeline. Relays 2, 3, and 4 control three solenoid valves, enabling localized regulation of water flow at specific sections of the pipeline. These solenoid valves operate based on commands from the system, opening or closing as needed to maintain safe and efficient flow conditions. When the system detects a significant drop-in flow rate or water level via the sensors, it can automatically initiate valve closure to isolate the affected section, preventing further losses.

Overall, this system effectively combines real-time sensor monitoring with automated device control, supported by graphical visualization tools. This integration enables timely detection and mitigation of pipeline leaks, ensuring operational efficiency and enhancing system safety.

3. Results and Discussion

This section presents and analyzes the experimental results obtained from the oil pipeline monitoring system. The findings include real-time flow rate and liquid level measurements, and leak detection performance. The results are interpreted in the context of system design objectives, sensor accuracy, and the effectiveness of the system. Comparative insights and implications for practical implementation are also discussed.

3.1. Sensor analysis of oil flow rate in a leaking pipeline

Figures 4 and 5 present the sensor-based analysis of oil flow rate behavior and fluid level variations in response to pipeline leakage. In accordance with the continuity principle, the flow rate measured within the pipe should match the volume change observed in the receiving tanks. Any discrepancy between these two parameters is indicative of leakage within the system.

In Figure 4, all five flow sensors initially record a steady increase in flow rate to approximately 2 L/min. However, divergence occurs as simulated leaks are introduced. Around minute 25, Flow 3 (grey line) shows a sharp spike followed by a sudden drop, while at the same moment, Ultrasonic Sensor 2 (red line in Figure 5) shows a ~4 cm drop in liquid level—indicating a leak on the left branch of the pipeline. Similarly, at approximately minute 45, Flow 4 (yellow line) peaks at 2.4 L/min, followed by a noticeable decline in Ultrasonic Sensor 3 (green), suggesting leakage on the right branch. Additionally, between minutes 50 and 80, Flow 2 (orange) exhibits a gradual decline from 1.9 to 1.6 L/min. This trend coincides with a ~4 cm drop in Ultrasonic Sensor 1 (blue), signaling leakage in the central line of the pipeline.

The test fluid used in the experiment is Tawon cooking oil, selected for its industrial-like viscosity ($\mu \approx 50$ cP) and safety in handling, with a density of approximately 0.92 g/cm^3. The system incorporates five YF-S201 flow sensors (rated for 1–30 L/min) and three HC-SR04 ultrasonic sensors (range: 2–400 cm, resolution: 3 mm), all managed by an ESP32 microcontroller. Sensor data is sampled at a rate of 1 Hz and transmitted in real time to a web-based dashboard for visualization and monitoring.

To simulate leak events, needle valves positioned at three locations (left, center, and right) are manually opened in 30-minute intervals. Each leakage scenario is repeated three times to ensure consistency and validate sensor response. The ESP32 microcontroller algorithm compares the cumulative volume measured by the flow sensors with the change in fluid level from the ultrasonic sensors. A discrepancy greater than ±3% triggers a visual alert, flagging a potential leak. The characteristic trends in the sensor data—specifically, flow surges or drops without a proportional change in tank level—demonstrate the system's effectiveness in identifying leakage events.

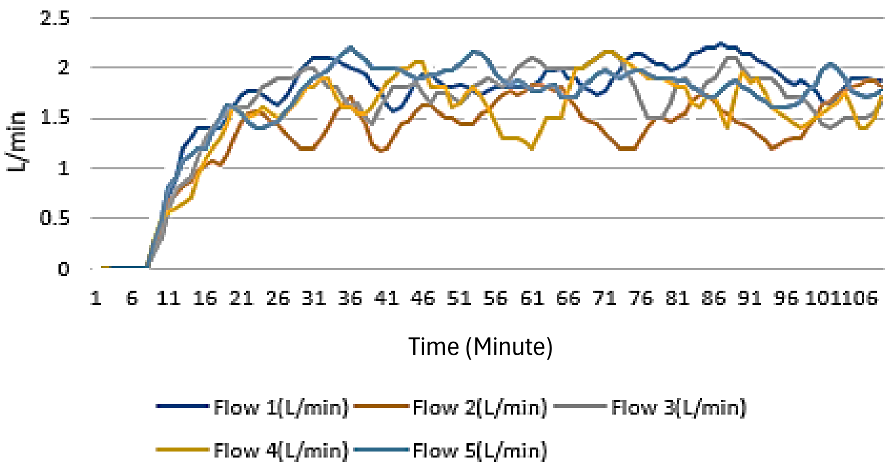


Figure 4. Graph of oil flow rate variations (flow 1 - flow 5) showing leakage

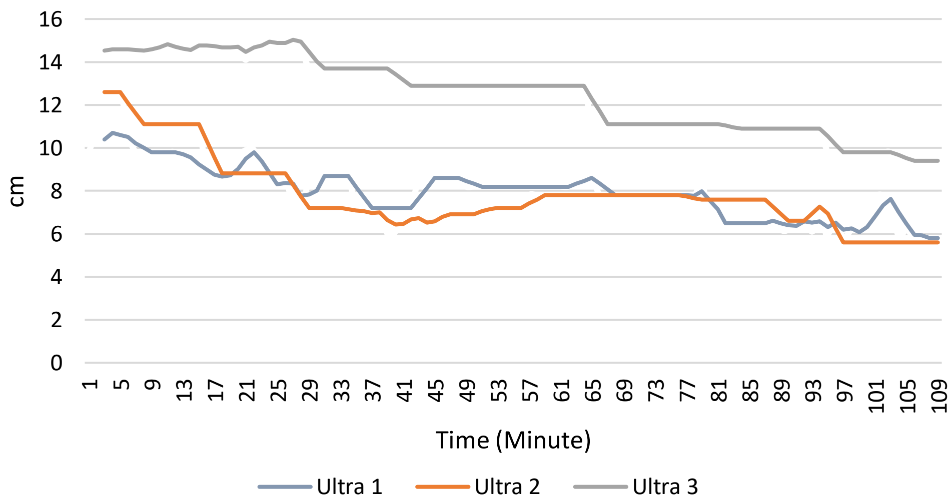


Figure 5. Ultrasonic sensors showing leakage

The results clearly confirm leakage occurrences in the left branch, right branch, and central pipeline, as shown by the synchronized changes in flow rate and tank level readings.

3.2. Oil flow rate sensor analysis on non-leaking pipes

Figure 6 and Figure 7 illustrate the behavior of oil flow and tank fluid levels under non-leaking conditions, serving as a baseline reference for the system's performance. The simulation graph includes two main parts: (Figure 6) data from the five YF-S201 flow sensors and (Figure 7) readings from the three HC-SR04 ultrasonic sensors. These measurements collectively demonstrate system stability and confirm the absence of any leakage throughout the duration of the test.

All five flow sensors (Flow 1 to Flow 5) display consistent flow rates fluctuating modestly within the range of approximately 1.5 to 2.1 L/min. This slight variation falls within the acceptable range for steady-state conditions and is consistent with the operational tolerance of the sensors. Simultaneously, the ultrasonic sensors exhibit minimal deviation: Ultra 1 sensor shows a slight downward drift of less than 1 cm, Ultra 2 sensor maintains a nearly constant fluid level around 14 cm, and Ultra 3 sensor oscillates gently between 13 and 14 cm without any significant step changes. This stable pattern indicates that the tanks are neither overfilling nor depleting unexpectedly, which confirms that the system is in a leak-free state.

The coherence between stable flow rates and nearly constant tank levels reflects the principle of mass conservation. In a sealed, non-leaking pipeline, the volumetric flow entering the system should equal the volume accumulated in the storage tanks, with negligible discrepancy. This is the expected behavior in an optimized system where pressure is retained, flow paths are fully enclosed, and no fluid is lost.

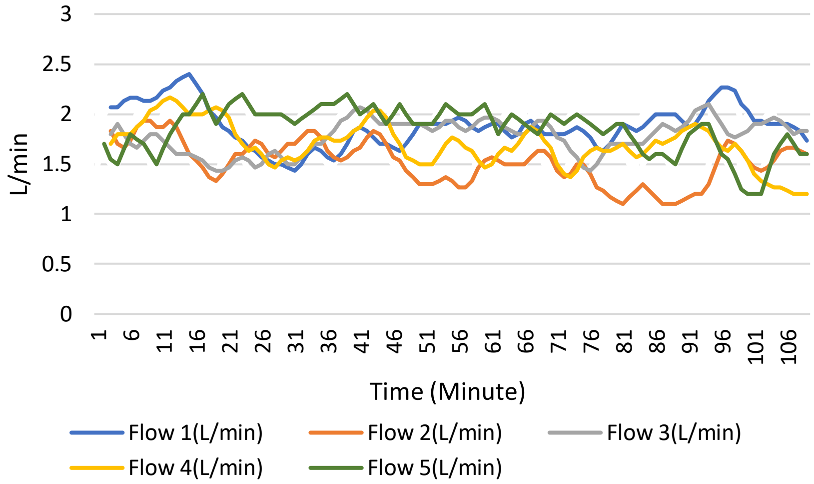


Figure 6. Measurement from water flow sensor and non-leaking condition

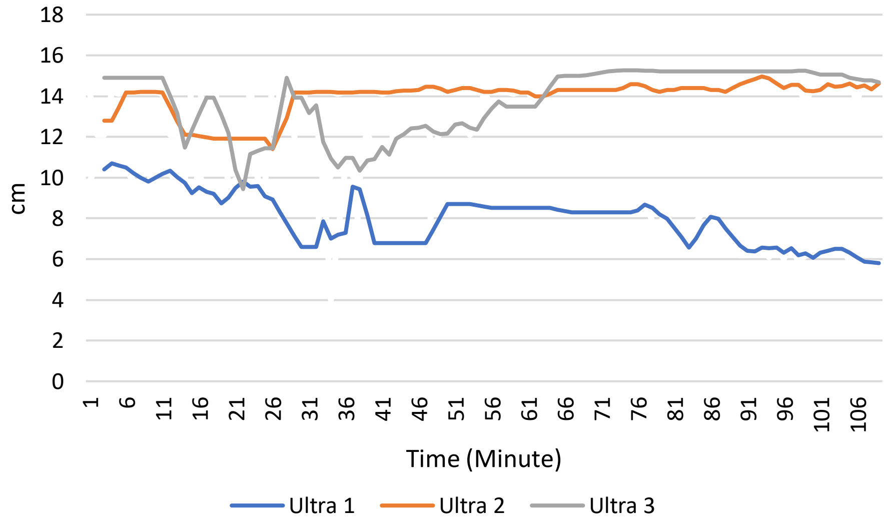


Figure 7. Measurement from ultrasonic sensor and non-leaking condition

Comparable baseline studies in existing literature often use high-precision ultrasonic flowmeters and level gauges, and validate non-leak conditions through pressure-hold tests in accordance with industry standards such as ASTM F2164 [16]. These tests typically accept only minor fluctuations within the combined instrumental uncertainty. Any deviation beyond these thresholds is flagged as a potential leak. Given that the flow and level data in Figure 6 and Figure 7 remain well within the acceptable tolerance limits, the system's leak-free performance is confirmed. This dataset establishes a reliable benchmark for comparison in subsequent experiments involving induced leak conditions, thereby enhancing the robustness of the overall leak detection methodology.

4. Conclusions

The experimental results confirm that the proposed IoT-based pipeline monitoring system effectively distinguishes between leak and non-leak conditions. Under induced-leak scenarios (Figure 5), three distinct time intervals showed clear discrepancies between the cumulative flow data from the YF-S201 sensors and the corresponding tank level changes measured by HC-SR04 ultrasonic sensors. These mismatches reliably signaled leaks in the left, right, and central sections of the pipeline. In contrast, during the non-leak condition (Figure 6), all flow sensors maintained stable readings between 1.5 and 2.1 L/min, while tank levels remained virtually unchanged—indicating strong mass balance and confirming leak-free operation. The experiment utilized Tawon cooking oil ($\rho \approx 0.92$ g/cm^3; $\mu \approx 50$ cP) to simulate industrial-like flow behavior, with all sensors sampled at a 1 Hz frequency by an ESP32 microcontroller. The embedded algorithm applied a ±3% threshold to detect flow-versus-volume inconsistencies, triggering leak alerts when exceeded. These results demonstrate that the instrumented system meets industry standards for leak detection: it remains stable during normal operation and responds rapidly when continuity is disrupted, confirming the reliability and real-time effectiveness of the monitoring platform. Beyond validating functionality, the study also reveals several practical advantages. First, the dual-sensor architecture—combining flow rate and level measurements—adds redundancy and reduces the risk of false alarms due to single-sensor errors. Second, the 1 Hz data acquisition and on-board processing enable detection of leaks in under a minute, aligning with standard industrial response times. Third, the system's cloud-based dashboard allows maintenance personnel to access real-time diagnostics remotely via any web-enabled device, enabling faster and more informed decision-making. Future developments will focus on extending the system to longer pipeline segments and incorporating pressure sensors to support leak localization. Furthermore, the integration of machine learning algorithms trained on high-resolution data could enhance the system's capability to classify leak severity automatically, further increasing the autonomy, intelligence, and robustness of the platform.

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