*Nigerian Journal of Technology (NIJOTECH)*
*Vol. 43, No. 3, September, 2024, pp.518 - 525*
*www.nijotech.com*

*Print ISSN: 0331-8443*
*Electronic ISSN: 2467-8821*
*https://doi.org/10.4314/njt.v43i3.14*

# A FUEL PIPELINE MONITORING AND SECURITY SYSTEM USING WIRELESS SENSOR NETWORKS (WSN)

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**ARTICLE HISTORY:**
**Received:** 17 April, 2024.
**Revised:** 01 August, 2024.
**Accepted:** 14 August, 2024.
**Published:** 20 September, 2024.

**KEYWORDS:**
Environmental Protection, Flow Rate, Leakage, Localization, Monitoring, Pipeline, WSN.

**ARTICLE INCLUDES:**
Peer review

**DATA AVAILABILITY:**
On request from author(s)

**EDITORS:**
Chidozie Charles Nnaji

**FUNDING:**
TETFund through the Institution Based Research (IBR) grant

## Abstract

*Pipeline infrastructure plays a critical role in the transportation of vital resources, including oil, gas, and water. However, pipeline failures and leaks can have devastating consequences, resulting in environmental damage, economic losses, and risk to human life. Traditional methods of leak detection, such as visual inspection and pressure testing, are often time-consuming, labor-intensive, and unreliable. With the advent of wireless sensor networks (WSNs), there is an opportunity to revolutionize pipeline monitoring and leak detection. In this paper, we present a system that can monitor and detect leakage early, to enable engineers carry out prompt maintenance. This is made possible by the use of a network of nodes in a WSN, placed along a pipeline, each of which is capable of measuring and reporting varying flow rates, indicative of possible leakages. The system design consists of three major layers namely, the nodes layer, the cloud layer (for data logging), and the reporting layer. Tests were conducted under various conditions. The results show that with no leakages, the average flow rates for nodes 1, 2, 3, and 4 were 16.89747978, 16.89935602, 16.90978163, and 16.93380634 respectively. Furthermore, percentage flow rate differences of -0.02550353, 29.959675, and 30.3944134 were recorded for nodes 2, 3, and 4 respectively, after leakages occurred. The high values of the percentage difference for nodes 3 and 4 indicate a significant discrepancy in flow rate, worthy of physical inspection. The system is capable of detecting faults and leakages, even in the event of sensor failure, or network disruption.*

## 1.0 INTRODUCTION

Pipelines serve as an effective means of transporting oil and gas from one physical location to another, such as from one refinery to another [1]. The reliable and efficient transportation of vital resources, such as oil, gas, and water, is crucial for economic growth, energy security, and environmental sustainability. Pipelines are a critical component of this infrastructure, spanning thousands of miles worldwide. However, pipeline failures and leaks can have catastrophic consequences. Oil spills and gas leaks can contaminate soil, water, and air, causing long-term ecological harm. Also, pipeline failures result in costly repairs, lost productivity, and revenue decline. In addition, risk to human life: Leaks can lead to explosions, fires, and exposure to toxic substances, posing significant risks to human health and safety.

One of the critical needs of countries such as Nigeria, with oil and gas deposits spanning the landscape, and which make use of transmission as well as distribution

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***HOW TO CITE:***
Ezeja, O. M., and Nwobi, C. G. "A Fuel Pipeline Monitoring and Security System using Wireless Sensor Networks (WSN)", *Nigerian Journal of Technology*, 2024; 43(3), pp. 518 – 525; https://doi.org/10.4314/njt.v43i3.14

pipelines for transportation of such fluids, is the protection of such pipelines, in addition to maintaining the integrity of same. In such countries that produce oil and gas, these networks of pipes are crucial for the effective transportation of the fluid, and in most cases, this invariably affects the national economy [2]. Due to the fact that these pipelines used for the transmission of oil and gas are normally operated at high pressure, any failure or breakdown experienced along the pipeline would usually constitute a health risk to the people residing around the area, and this also badly affects the economy. The challenge is to be able to continuously observe the pipelines and promptly report any leakage [3].

The presence of heavy metals, which often result in the bio-accumulation of unwanted substances in crops which humans un turn consume, are often characteristic of oil spills, and are known to be dangerous to the health of humans [4]. It is known through relevant reports that exposure to these harmful substances can lead to acute renal failure [5]. One of the most toxic of these substances is mercury [6] and is also among the highly bio-concentrated metals in the human food chain. The Environmental Protection Agency (EPA) has classified organic form of mercury that is known to exist in crude oil to be a likely cause of cancer [7].

Recent advances in wireless sensor networks (WSNs) offer a transformative solution for pipeline monitoring and leak detection. WSNs enable real-time monitoring, remote data transmission, and advanced analytics, making them an attractive solution for pipeline operators and managers. With the advent of what is now referred to as emerging technologies, the oil and gas industries are also beginning to consider Internet of Things and big data [8]. One of the fundamental requirements for effective management of pipelines for fluid transportation, is making accurate and real-time measurements of critical flow characteristics using embedded sensor units, especially when incorporated with internet of things, (IOT) [9]. Pipelines are regarded as the most effective method of delivering substantial quantities of oil, refined petroleum products, and natural gas over land [10]. Pipeline monitoring and inspection, is usually carried out to identify the locations along the path of laid pipes that have defects, and obtain an accurate measurement and assessment of the defects so that human operators can swing into action to prevent further damage to the pipelines and environment [11]. Some work has been done in the area of finding solutions to the problem of pipeline leakages through monitoring them using WSNs. The basic role of a WSN is to harvest and transmit data between nodes in order to meet the requirements of a particular system design [12].

Oil, gas, and water pipelines are regarded as one of the most critical infrastructure in many countries . Linear wireless sensor networks are used for monitoring critical economic infrastructure with linear topologies like oil and gas pipelines [13]. In [14], a sensor-based solution referred to as Sensor-based Pipeline Autonomous Monitoring and Maintenance System (SPAMMS) was developed. It has sensing technologies that are robot agent based, for monitoring of pipelines. The solution has been compared with some cutting edge WSN based system designed for monitoring pipeline systems. In [15], the authors showed the significance of a new category of Internet of Things known as the Internet of Underwater Things (IoUT). The researchers that developed this categorized the different types of underwater applications. The authors in [16] carried out an extensive documentation of the recent development and challenges, as well as the taxonomy and requirements for a WSN in the oil and gas industry. Furthermore, a group of researchers in [17] presented a system called Wireless Gas Safety Management System (WG-SMS) aimed at sensing Hydrogen Sulphide ($H_2S$) gas and also attempting to identify workers who are exposed to danger. [18] proposed a solution known as “SimpleMote”, which is a technique that depends on a sensor network installation for detection of oil and gas pipeline leakage.

Also, in [19], the authors attempted to x-ray as well as proffer solutions to the many challenges frustrating the effective deployment and use of WSN technology in the Niger Delta region of Nigeria, where oil and gas pipelines are massively laid. [20] also shows a leakage detection technique using pressurized fluid by transform analysis. In [21], the authors developed a novel solution for controlling and monitoring pipelines. Some of the essential components of this system include a mobile application, a wireless connection of monitoring elements, as well as isolation valves. From time to time, the mobile application receives alerts, particularly at the instance of observation of a leak, and it has in it the ability to shutdown remotely, valves that are linked to that suspected location.

Other works like [22] - [29] have also discussed related aspects of the development of systems that can carry out monitoring of pipes for leakages and bursts.

Traditional leak detection methods, such as visual inspection, pressure testing, and acoustic sensing, have limitations which include, but are not limited to being time-consuming and labor-intensive, inherent high false alarm rates, and adopting reactive rather than proactive approach. This article presents a pipeline leakage detection system that leverages WSNs to provide real-time monitoring and detection of leaks. Our system integrates, advanced sensing technologies wireless communication protocols for real-time data transmission, cloud-based data analytics and visualization platform. This system offers several benefits, including enhanced safety and reliability, reduced downtime and maintenance costs, and real-time monitoring and decision-making capabilities. In this work, we will delve into the design, implementation, and performance evaluation of our pipeline leakage detection system.

## 2.0 METHODOLOGY

The system design involves setting up a pipeline structure, connected to a supply, along which are placed sensor nodes at different points, and also taps strategically located between the nodes to serve as leakage points. Placing the sensors at equal intervals along the pipeline ensures efficient optimization of communication between nodes, thereby minimizing interferences and ensuring reliable data transmission. Putting on the taps therefore is used to simulate points of leakage.

### 2.1 The Layers of the System

The system consists of three major layers: The Nodes layer, the Cloud layer (for data logging), and the Reporting Layer. Figure 1 shows a typical sensor node attached to a pipeline cross-section in the WSN

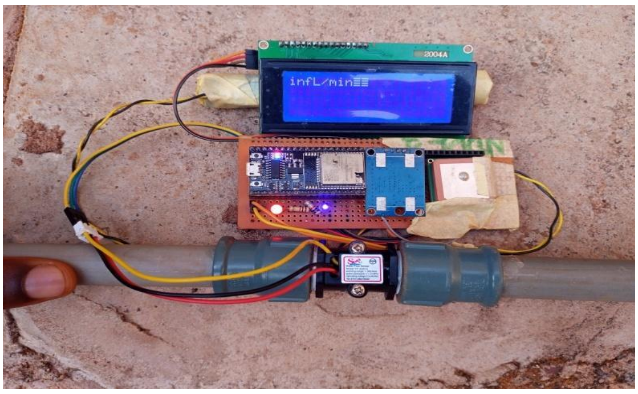

**Figure 1:** One of the nodes in the pipeline cross section

The Node Layer consists of nodes which are utility electronic devices embedded at different points along the pipeline. Each node consists of the ESP32 microcontroller, a flow rate sensor, a NEO-6 GPS module, a power unit, and indicators (LEDs and LCDs). YF-S402B flow rate sensor is a flow rate sensor installed directly into the oil line. This became the sensor of choice since the fluid used for the experiment is water.

Water and fuel have similar density and viscosity properties, making water a suitable substitute for fuel. Also, considering the financial constraints, water is inexpensive and readily available, reducing experimental costs. Moreover, water flow rates can be easily scaled up and down to simulate different fuel flow rates. This flow rates rely on the kinetic energy of the flowing fluid, rather than the physical properties of the fluids themselves. Another reason for the use of water is environmental concerns. Using water reduces the risk of environmental pollution and contamination. Water is also safer fluid to work with than fuel, which can be flammable and hazardous, again considering the amount of funds available for the research.

YF-S402B features a pinwheel sensor to gauge liquid movement. Additionally, it incorporates a sealed magnetic Hall Effect sensor that generates an electrical pulse for each rotation. The sensor includes three cables: red (a 5-24V DC power line), black (for ground), and yellow (for the Hall Effect pulse output). As the fluid moves through the sensor, the pinwheel rotates to generate pulses. The pulse rate varies linearly with the flow rate of the fluid in the pipe. By tallying these pulses, we can estimate the flow rate of the oil. Given that the pulse rate varies directly to the flow rate, a drop in average flow rate over a period could signify either of the following:

- There was a general drop in the transmission rate from the oil transmitting station, in which case, no alarm needs to be raised.
- A leakage or intentional breakage of the pipeline by vandals has occurred, in which case, the system should raise an alarm.

The system verifies which of cases 1 and 2 holds through the help of control nodes. A control node is, in all ways, just like every other node in the system. However, this node has been positioned to serve as a reference point for the rest of the nodes within the channel. Control nodes are situated at a point closest to the transmitting station. In a real-world scenario, this node is located at a place where the management can directly monitor it and should always operate at an optimal state, as it serves as the primary source of truth for the entire system. It is assumed that no leakage has occurred between the transmitting station and the control node; hence, the flow rates measured by this node should be reliable enough to be used as a




https://doi.org/10.4314/njt.v43i3.14

reference for the other nodes within the same channel. If the readings by any node vary substantially from those of the control node, it is an indicator that there is a leakage along the pipe, somewhere at a point between the first node that detected this drop and the node just before it.

Each node has an onboard GPS module that helps isolate the approximate location where the pipeline leakage occurred. This is known as localization. The NEO-6 GPS module uses a combination of signals from satellites to determine its precise location (longitude and latitude) on Earth. It receives signals from at least four satellites, calculates the time it takes for each signal to reach the module, and uses this information to triangulate its position. The choice of this module was inspired by the fact that it does not need an internet connection or phone signal to function, making it possible for the pipeline leakage detection system to still function effectively in regions without internet connectivity. Once we have detected that a leakage has occurred, the system then isolates the latitude and longitude data of the node that first recorded this drop. With the change in flow rate and location information detected, we can know the magnitude and location of the impact. If the detected change in flow rate is above our tolerable threshold, the system notifies us through the visualization portal.

**The Cloud Layer** - To reduce interdependencies within the system, we designed this system such that each node transmits its data directly to a cloud logging portal. An internet connection is however, required for this transmission to take place. Since the ESP32 microcontroller has an onboard Wi-Fi shield, there was no need for further implementations. For this project, we used the ThingSpeak Internet of Things (IoT) cloud solution to log the data. ThingSpeak provides Application Programming Interfaces (APIs) for devices to send data to its cloud servers, where the data can be stored and accessed without requiring custom implementation. Each of the nodes in the system communicates with its own ThingSpeak channel via an API (not to be confused with the pipeline channel).

**The Reporting Layer** - With each node's data on the cloud, the last phase of this system is the reporting layer. This layer consists of a custom dashboard that visualizes the geographic location of each node on a map. For this project, a Python script was implemented to handle the pulling of data from each node via the Requests library. The pulled data is then cleaned and transformed for visualization using the Plotly library. If leakage is detected that is beyond the set threshold, the location of the first node to detect this leakage is colored red to indicate leakage.

### 2.2 Sensor Calibration

The sensors were calibrated using a laboratory setup. A constant level tank and overhead tank (the feeder) were utilized to maintain a constant inflow and outflow of liquid to the system, ensuring a consistent flow rate. We determined the actual flow rate by recording the volume over time and then calculating the average. Subsequently, while maintaining the same setup, we re-measured the average flow rate using the flow rate sensors. In general, the sensor readings registered slightly lower than the actual flow rate, yet they closely resembled each other. To standardize the equation, we computed the average of these differences, resulting in the relationship:

$$Fa = 1.114Fm \quad (1)$$

where $F_a$ is the actual flow rate and $F_m$ is the flow rate measured by the sensor.

Ideally, determining a unique constant for each sensor would have been preferable. However, implementing this approach would introduce further complexities as we would need to adjust our code for each sensor.

## 3.0 RESULTS AND DISCUSSION

### 3.1 System Performance Evaluation

#### 3.1.1 Leakage detection accuracy

Tests were conducted on the system under various conditions, namely with leakage, and without leakage.

**Test Case 1:** Table 1 presents the results of the test when no leakage occurred. With no tap turned on to simulate leakage, the average flow rates for nodes 1, 2, 3, and 4 were 16.89747978, 16.89935602, 16.90978163, and 16.93380634 respectively. Leakage Status for all nodes returned as FALSE, indicating the absence of any leakage as there was no significant difference between the flow rate of node 1 (the reference node) and that of the rest of the nodes. The three nodes (nodes 2, 3, and 4) have percentage flow rate differences of -0.011103676, -0.072802874, and -0.214982151 respectively from the reference flow rate. This implies that there is no suspicion of leakage along the pipeline cross section since a fairly consistent flow rate has been maintained.

The visualization portal displays a map with markers representing the approximate location of each node. As depicted in Figure 2a, all markers are highlighted in green, indicating the absence of detected leakage.

**Table 1:** Aggregated view of the nodes when no leakage was detected

| | Node 1 | Node 2 | Node 3 | Node 4 |
|---|---|---|---|---|
| Average Flow Rate | 16.89747978 | 16.89935602 | 16.90978163 | 16.93380634 |
| Reference Flow Rate | 16.89747978 | 16.89747978 | 16.89747978 | 16.89747978 |
| Percent Difference | 0 | -0.011103676 | -0.072802874 | -0.214982151 |
| Leakage Status | FALSE | FALSE | FALSE | FALSE |
| Latitude | 6.872758 | 6.873006 | 6.873254 | 6.873502 |
| Longitude | 7.405135 | 7.409878 | 7.414621 | 7.419364 |

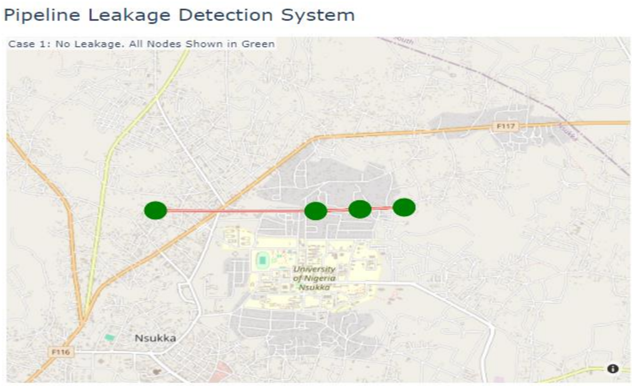


**Figure 2a:** Nodes in a channel with no leakage

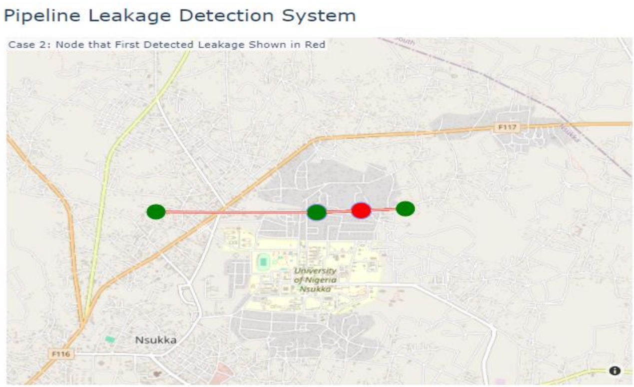


**Figure 2b:** Nodes in a channel with leakage

**Test Case 2:** In the second case, we tested the system under conditions where leakage occurred. To simulate this, we activated the tap after Node 2. As shown in Table 2, nodes 3 and 4 returned 'TRUE' for the leakage status. This is because after the tap is opened to simulate leakage, the flow rates for the next set of nodes (nodes 3 and 4) are expected to drop drastically. The other three nodes (nodes 2, 3, and 4) have percentage flow rate differences of -0.02550353, 29.959675, and 30.3944134. The high values of the percentage difference for nodes 3 and 4 indicate a significant discrepancy worthy of physical inspection. Consequently, Node 3 was automatically highlighted in red in the visualization portal to isolate it for physical inspection (see Figure 2b). Note also that the system does not highlight all other nodes following node 3 (say node 4) as red, even though they also have significantly reduced flow rates. This is because the first node to report a reduced flow rate represents the most likely area of leakage. This is the process of localization of possible burst or leakage along the pipeline.

**Table 2:** Aggregated view of the nodes when leakage was detected

| | Node 1 | Node2 | Node 3 | Node 4 |
|---|---|---|---|---|
| Average Flow Rate | 16.886194 | 16.89050078 | 11.827145 | 11.7537345 |
| Reference Flow Rate | 16.886194 | 16.8861942 | 16.886194 | 16.8861942 |
| Percent Difference | 0 | -0.02550353 | 29.959675 | 30.3944134 |
| Leakage Status | FALSE | FALSE | TRUE | TRUE |
| Latitude | 6.8730855 | 6.873006 | 6.873254 | 6.873502 |
| Longitude | 7.3926862 | 7.409878 | 7.414621 | 7.419364 |

The visualization portal also includes a time series chart displaying the average flow rate per node. Refer to Figure 3a and Figure 3b below for test cases 1 and 2, respectively. In the first case, Figure 3a shows that the flow rates at all the nodes are approximately equal to those of the control (node 1), signifying that there is no suspected leakage along the pipeline cross section. However, a look at Figure 3b shows a remarkable drop in the flow rates for nodes 3 and 4. This indicates a possible point of leakage located just before the first node that has a noticeable decrease in flow rate.

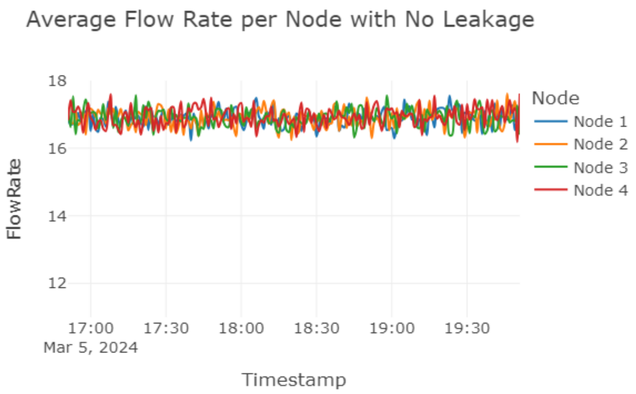


**Figure 3a:** Average Flow Rate per Node with no leakage

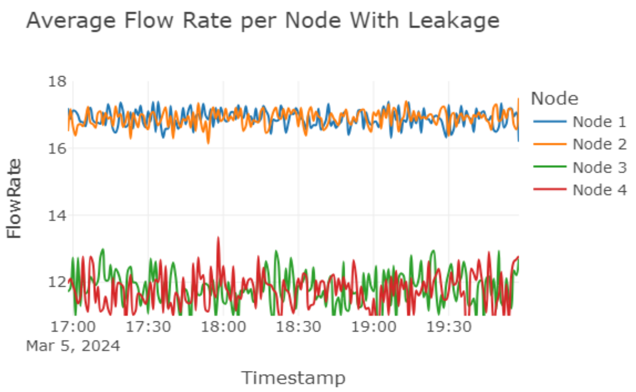


**Figure 3b:** Average Flow Rate per Node with leakage

### 3.1.2 Response time

In a steady state, the minimum estimated response time of the system is about 20 seconds from the time of impact, but this can vary, depending on factors such as internet speed, the magnitude of impact, and the cloud service utilized, among others. For instance, we used the ThingSpeak free plan, which has a maximum update frequency of 15 seconds, but other higher plans offered by ThingSpeak allow for even higher update frequency. In terms of the magnitude of impact, since the system checks for leakage by taking the average flow rate over time, an impact with a higher magnitude would result in a faster negative mean shift due to outlier influence. The response time can be adjusted to almost real-time. However, for a more reliable result, it is better to look at the system from a longer time window to minimize false positives due to noise.

### 3.1.3 Fault tolerance

Since the system was built on a chained architecture, it can operate effectively in the event of sensor failure or network disruption. When a node fails to detect leakage due to sensor failure or a network glitch, other nodes in the channel can still detect it. The inclusion of multiple nodes within one channel aims to facilitate the isolation of the location where the leakage occurred. The only consequence would be an increase in the range of the impacted area. As depicted in Figure 4, a leakage in the system will be detected not only by Node 2 but also by other nodes down to Node N. However, to facilitate the isolation of the point of leakage, the region between the Control Node and Node 2 will be isolated. If the sensor at Node 2 fails, Node 3 will become the next nearest node to the point of impact, and the region between the Control Node and Node 3 will be isolated. This, however, implies that the total isolated area for inspection will increase. An exception to this fault tolerance arises if the failure affects the control node itself. A failure at this point will result in errors at the other nodes, as they rely on it for reference. The longitude and latitude coordinates of the nodes make it easy to pin-point the leakages.

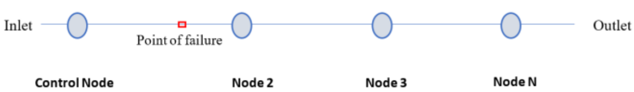


**Figure 4:** Localization of leakage point.

## 3.2 Scalability and Flexibility

This system was designed bearing in mind the importance of scalability and flexibility in order to guarantee future expansion or modification. For instance, to add more nodes to a channel, all that will be required is a ThingSpeak channel to communicate with this node. Each ThingSpeak channel has a channel ID, READ and WRITE API Keys. We will need the WRITE API key, as well as the channel ID in the configuration of the node. We will also need to tie this node to the control node to which it belongs. Next, we update the Python script to include the channel ID and READ API key for this node so that data from this node is included in the visualization portal.

Also, it is very easy to add a whole new channel. Recall that a channel refers to a system of nodes that run along a pipeline without any branching. To introduce a new channel, we will need a control node for the channel. This needs to be the first node from the point where the branching occurred. Each subsequent node in the channel needs to be linked to the control node so that they can take the readings of the control node as a reference.

## 4.0 CONTRIBUTION TO KNOWLEDGE

In carrying out this research, one of the major contributions of this work is the fact that we actually implemented the visualization of the system in the form of a dashboard. A number of works in literature only mentioned how the system can be implemented without practically incorporating such implementation in their design. Furthermore, we also designed a circuit for the realization of the design. In addition, we also integrated the system with ThinkSpeak, and with this, we have demonstrated an easier way of implementing such systems without one needing to set up separate server. ThinkSpeak is an open-source IOT (Internet of Things) platform that allows users to connect and manage devices, collect data, and build applications. It functions as a server, providing a cloud-based infrastructure for IOT projects. As highlighted previously, this data logging solution provides Application Programming Interfaces (APIs) for devices to send data to its cloud servers, where the data can be stored and accessed without requiring custom implementation.

## 5.0 CONCLUSION

This system, which has the capacity to effectively monitor pipelines, detect and accurately localize leakages, finds usefulness in pipeline surveillance and maintenance work. This design can be used to successfully detect and accurately localize points of leakage along a fuel pipeline. It helps in reducing the impracticable labour of using personnel to inspect the entire cross section of pipelines when leakages are suspected. It brings with it (as an improvement over existing technologies), the ability to still carry out detection and localization without internet service as it makes use of satellite technology. The system is also scalable and flexible, as discussed. However, this is a mere structural design issue. Our system was largely simplistic and enabled us to directly screw the meters along the axis of the pipes, but this may not be possible for larger pipelines that may require more advanced coupling mechanisms. However, what matters is that the fluid's direction of flow is orthogonal to the axis of rotation of the turbine, and enables fluid movement through the pipe to impact the turbine blades, causing it to rotate. Whichever final design is adopted depends largely on the designers, as long as the underlying working principles of the meter are not affected.

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