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Original Research Article

LoRaWAN-based Petroleum Pipeline Leakage Detection System Using Pressure Profile under a Pump Proximity Effect Condition

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Abstract

Leakages in pipeline is an important problem that can occur at any stage of the pipeline lifespan due to ageing, improper installation, or human related factors like bunkering or vandalization. Several invasive and non-invasive techniques are being used which have proven to be successful. However, this study focuses on leakage in an area of the pipeline network that is most often overlooked. This area is within the first 100 meters of the pipeline network to the excitation pump and is often prone to leakages due to high pressure. This study shows that even at no leak conditions pressure profile of a short pipeline in a closed loop configuration can vary by as much 59.93 percent. The study also examined the impact of single leak, double leaks, and triple leaks on the pipeline network with pressure loss compared to the no leak condition ranging from about 10 percent to as high as 60 percent.

Keywords: LoRaWAN, LoRa, pump proximity effect, pressure.

INTRODUCTION

Petroleum pipelines are an integral part of global trade and play a very pivotal role in the global economy by enabling the transportation of crude oil and refined products across vast distances. Pipelines are also regarded as the safest and most efficient means of petroleum products transportation particularly over land [1]. Aside from this, the economy of scale also ensures that in the long run, it remains the cheapest way of transporting petroleum products [2].

However, oil pipelines face several challenges which can erode every benefit they present if not properly managed. They are usually vulnerable to leaks especially when poorly designed or maintained. The leaks can result in severe environmental damage, costly cleanup efforts, fire, and reputational damage to the companies that operate them. Apart from the problem of leakages, estimates show that between 5 to 7 percent of global oil production amounting to about $133 billion is stolen along the oil value chain annually [3]. Also, in developing economies, oil theft and illegal bunkering are often perpetrated at a scale that is large enough to retard the economy. These acts are usually carried out by organized criminal groups and other corrupt entities in communities that play host to oil pipelines. In Nigeria for instance, oil theft is estimated at around 400,000 barrels per day amounting to an annual loss of $12 billion and tax revenue loss of US$20 billion [4]. From the foregoing, it is evident that an efficient and reliable leak detection and localization system is needed for both environmental and economic reasons.

Fortunately, several engineering applications today are leveraging the immense benefits of the Internet of Things (IoT) to automate activities that were hitherto done in stereotypes. IoT technology allows for the interconnection of sensors and actuators that share data over the internet [5].

A typical IoT-based leak detection system as shown in Figure 1 will consist of sensor nodes that measure changes in pipeline parameters and a communication link to provide wireless connectivity. The wireless link forms the backbone of the network and helps to transmit information from sensor nodes to a remote server that carries out data processing and analytics. In recent years, the emergence of low-power

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wide area network (LPWAN) technologies has opened new possibilities for remote monitoring and control-related applications [6]. One of the most popular of this technology is the Long-Range Wide Area Network (LoRaWAN). Their increased popularity is hinged on their unique ability to provide long-range, low cost and energy-efficient wireless connectivity for IoT applications. The LoRaWAN operates a star topology and only requires individual nodes to transmit information to the network server through a gateway [7]. Since pipeline networks usually span several hundred or thousands of kilometers, the low cost and long-range connectivity provided by LoRaWAN is an extra motivation for the choice of the technology [8].

In this study, we specifically deployed LoRaWAN, coupled with pressure sensors to investigate the use of pressure profiles in detecting leakages in the petroleum pipeline network. While the study can be applicable to any section of the pipeline network, our specific focus is on the first section of the pipeline network structure. This section typically comprises approximately, the first 100 meters of the pipeline network succeeding the excitation pump. The area is of greater interest due to its predisposition to close pump scenarios which can also be referred to as the pump proximity effect, or the near-pump pressure drop effect. The pump proximity effect as defined in this study refers to situations where the pressure changes due to the interaction between the pumping action of the pump and the flow dynamics within the pipeline, thus making it more challenging to distinguish leakage-induced pressure variations from normal operational fluctuations.

Apart from the problem of the close pump scenario, this pipeline section is closest to the high-pressure pump, they are more subjected to extreme pressures and hydrodynamics vibration than any other section of the pipeline structure. Due to this intense pressure, leaks are more likely to occur more often than in any other section of the pipeline network.

To achieve the aim of this study, real life experiments were carried out on pipeline testbed that was modelled with 50 meters stretch of one inch pipeline network. Pressure sensors were attached, and leakages emulated. The pressure profile of the network was obtained under leak and no leak conditions and result analysis carried out. By incorporating advanced algorithms and machine learning techniques, the system aims to improve the accuracy and reliability of leakage detection in close pump scenario. Our specific contribution in this study is in the development of robust and efficient leakage detection systems for petroleum pipelines. These systems have the potential to minimize the environmental impact, mitigate economic losses, and enhance the overall safety and security of pipeline operations.

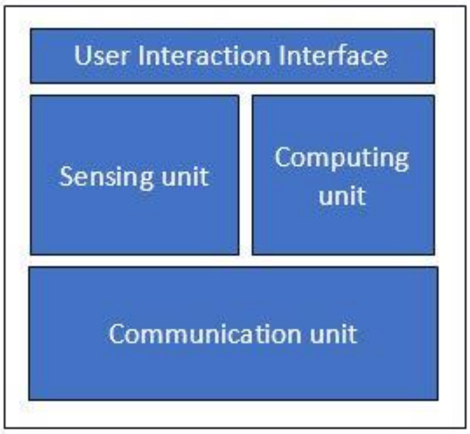

Figure 1: Building block of a leak detection system

BACKGROUND TO THE STUDY

The transportation of petroleum products through pipelines is a critical aspect of the oil and gas industry due to the long-term economic benefits of this mode of oil transportation. However, ensuring the safety and integrity of these pipelines is of utmost importance to prevent environmental hazards, financial losses, and potential disasters. Pipeline leakage detection systems play a vital role in early detection and mitigation of leaks. However, traditional systems face challenges related to accuracy, cost, and real-time monitoring capabilities. Subsequently, several other alternatives have been proposed to mitigate the challenge of pipeline leakages. Authors in [9] presented a broad review of some of the popular pipeline leakage detection system. The authors classified the pipeline detection methods into externally based methods, visual or inspection-based methods and internally or computationally based methods. The externally based methods include the use of acoustic sensors, fiber optic sensing cables, vapor sensing tube and liquid sensing tube.

The visual or inspection methods involve the use of human or trained dog and the use of UAVs or robots. The computational based methods include the use of balancing systems, real time transient modeling, pressure or flow monitoring, negative pressure wave and statistical analysis. In a similar survey conducted by authors in [10], the strength and weakness of each of these methods were discussed as no single method is completely perfect and flawless. For example, the authors noted that the external methods are well used in industrial application. However, some of them have slow response time while others are difficult and expensive to install and maintain. Some like the ground penetration radar system have their accuracy greatly dependent on the nature of the soil while others like the infrared thermography are incapable of measuring very small leakages. The visual methods of monitoring are largely human dependent, unscientific and the least efficient, though the system has the least technical requirements.

The internal methods can detect very tiny leaks since they are usually in contact with the fluid of interest. However, as noted in [10], these methods are very prone to false alarms and the data can be easily adulterated by environmental noise.

Specifically in this study, pressure profile which is a subclass of the internal methods was employed in detecting leakages in pipeline. Our focus however is on the initial offset of the pipeline network due to the peculiarities of these section of the pipeline. Authors in [11] investigated fluid-structure interactions in pipelines during the period of unsteady recirculating flows with a view of gaining insight into mass-momentum coupling in pipelines during fluid propulsion. The study identified the presence of a consistent unsteady reticulation zone with incoherent fluid dynamics. Mitigating techniques for pressure drop reduction pattern in oil-water pipeline was studied by [12].

The study in [13] also identified a transient period of high pressure and high flow rate instability in centrifugal pump start up process due to the rotational inertia of the electric motor employed. Authors in [14] studied the pressure profile of short pipes with leaks using transient mathematical models. The author specifically studied the effect of convective fluid flow on the pipe pressure profile. The study revealed that for short pipe, leakages can cause pressure increase at leak location. The study in [15] employed the use of neural network and particle swarm optimization technique to model pipeline pressure drop in extremely low temperature conditions in order to minimize energy usage cost. Pressure fluctuations within pipelines are influenced by a myriad of factors, often categorized as major and minor losses [16]. Fluid viscosity stands as a significant factor; as viscosity increases, frictional losses intensify, leading to elevated pressure drops. Notably, pipe surface roughness, especially prevalent in aging pipelines with scaling or corrosion, contributes to frictional resistance—though typically classified as minor losses [17].

Another source of pressure loss stems from the pipeline's length; longer pipelines inherently incur more significant frictional losses. Flow rate and pipe diameter also impact pressure drop, with higher flow rates and smaller diameters generating heightened turbulence, thus amplifying pressure loss. The presence of fittings, bends, and obstructions in the pipeline introduces supplementary resistance, further influencing overall pressure dynamics. Additionally, fluid properties, including density and temperature, exert their influence on pressure drop behavior. These factors are also highlighted in the Darcy–Weisbach equation given in equation (1).

$$\Delta h_f = f \frac{L}{D} \frac{v^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where Δh_f is the head loss, f is the friction factor, L is the pipe length, D is the pipe diameter, v is the average fluid velocity and g is the gravitational acceleration.

In terms of communication protocol, the LoRaWAN protocol [6, 18] used in this work has been extensively used in literature for leakage monitoring. Authors in [19] proposed the use of LoRaWAN technology for a near real-time leakage detection system in water pipeline. The study analyzed the suitability of several low power wide area network technology like Sigfox, Narrowband IoT, and LoRaWAN with a view of establishing their suitability as better alternative to GPRS using a linear energy-consumption model. The study identified a few technical limitations of the low power wide area technologies but were better alternatives to GPRS due to longer operational time which could exceed 5 years. Also, out of the three LPWAN technologies considered, LoRaWAN at a mean power consumption of 103.6 mW had the lowest energy consumption making a better candidate for the pipeline leakage monitoring application.

Also, authors in [20] employed the use of LoRaWAN for leakage detection in housing complexes. The study through simulation examines the reliability and scalability of an integrated LoRaWAN system in household water leakage management. The study varied the number of nodes as well as the size to test the limit of LoRaWAN in such application scenario. The study revealed that the LoRaWAN technology can be efficiently used for water monitoring as well as leakage detection in residential complexes.

The study in [21] developed an IoT-based oil leak detection system. The developed system known as iLoLeak-detect was proposed to validate the suitability of LoRa technology in the midstream sector. The study revealed that iLoLeak-detect yielded accuracy of up to 90.83 percent in real-time operations.

The study conducted in [22] equally developed a LoRaWAN based IoT smart metering system for water management. The study specifically tested the suitability of the wide area network in terms of data transmission, reliability, and modularity. Overall, the study reported a detection success rate of 95 percent.

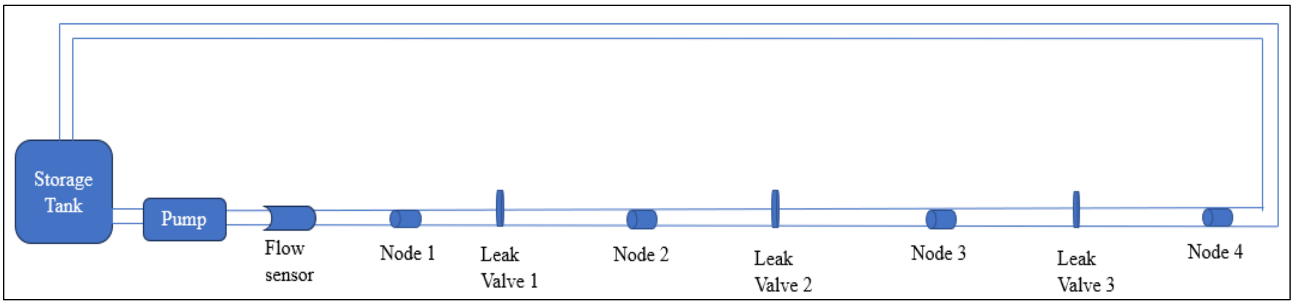

Figure 2: Leak detection system experimental setup [23]

In [24], the authors employed edge processing in a LoRaWAN based leakage detection system in water distribution networks while a similar approach employed in [25] for water monitoring yielded an equally reliable result. Consequently, the consensus in LoRaWAN-related survey is that the deployment of the technology is effective and more importantly sustainable [26].

There are few literatures on the near pump effect in literature as the phenomenon is more popular in the field of nano-materials [27, 28]. However, a study conducted investigated the impact of proximity effects on offshore intake wells in close vicinity [29].

METHODOLOGY

The aim of this study is to study the pump proximity pressure effect in pipelines. The phenomenon can influence the pressure profile of pipeline when they are within about 100m of the pump. To investigate this phenomenon, we setup an outdoor experiment as shown in Figure 2. The entire setup consists of a pipeline network of 100 m length connected in a closed loop configuration. The entire setup as shown in Figure 2 consist of a storage tank, an electric pump and a flowrate sensor to measure the fluid velocity. The pipes used for this experimentation are 1 inch in diameter with nodes created at each junction where two pipes are joined.

As shown in Figure 2, a total of 4 nodes were created on the entire pipeline network. The nodes are equidistant from each other with one each at the network entry and exit point and the remaining two nodes at midpoints of network. At each of the four nodes, pressure sensors were installed. The pressure sensors were connected to a LoRaWAN based IoT system as shown in Figure 3. The IoT system is based on TTGO LoRaWAN module, and an electrical power system. The LoRaWAN module consists of an ESP32 microcontroller and the LoRa SX1276 low power chip configured to use a spreading factor (SF) of 7 due to its shorter time on air and higher data rate. The SF7 was also used for the experimentation due to the short distance involved. The entire setup was powered by 3 lithium battery.

A LoRaWAN gateway was used for data aggregation. The gateway setup was similar to that of the transmitter. The gateway uses an internet shield to transmit data to a server where data were acquired and analyzed. The demonstration procedure starts with the pump which pumps water through the pipeline network. The water flows from the tank through the pipe and back to the storage tank in a closed loop configuration. The pressure sensors attached to each of the four nodes measures the pressure at each node location and transmit the data over LoRaWAN to a receiver.

Timestamps for the received data were collected so each data points could be evaluated. First the pipeline was run at no leak conditions and data collected. This was repeated 5 times and an average evaluated. Next, each of the leak valve as shown in Figure 2 were opened one by one for each experiment. The impact of each individual leakage valve on the pressure profile of the network was recorded. Furthermore, the experimentation also studied the impart of multiple leaks. First two leaks were introduced and lastly all three leak valves were opened, and the impact noted.

The pressure was calculated using the Bernoulli’s principle since for incompressible fluid both pressure and kinetic energy is expected to be constant in a streamline. This is as given in Equation (2).

$$P = E - \left(\frac{1}{2}\rho v^2 + \rho g h\right) \ldots\ldots\ldots\ldots\ldots.. (2)$$

Where P is the fluid pressure, E the mechanical energy per unit mass from the pump, ρ the fluid density, v the fluid velocity and h the fluid high above the reference. The flowrate sensor just after the pump was able to measure the fluid velocity and mechanical energy obtain from the pump details. For the experiment, a 1 HP pump was used to the scale of the experiment.

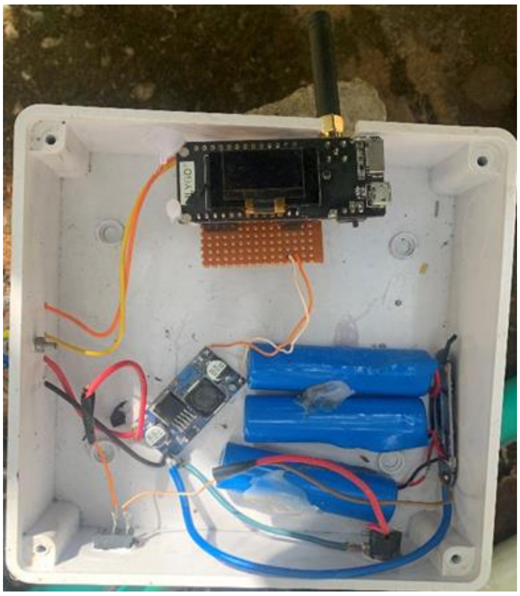

Figure 3: LoRaWAN transmitter

RESULTS

To understand the impact of the near-pump proximity effect on the pipeline network, different experimental setup was considered. In the first scenario, the pipeline network was operated in a no leak condition and pressure reading taken. Next, a single point leak was created in leak valve 1, leak valve 2 and leak valve 3 with the impact of each individual leak on the network measured. The result for this first stage experimentation is as shown in Figure 4. Ideally, it is expected that in a typical pipeline network of such short length, the pressure across the entire length of the pipeline should be relatively constant if there are no leaks.

However, from the result in Figure 4 it is noted that this was not the case. A pressure drops of 36.7 percent was observed between node 1 and 2, 52.06 percent drop between node 1 and 3, and 59.93 percent drop between node 1 and 4. Also, the highest pressure-drop of 36.7 percent between successive nodes occurred between node 1 and 2 which are the closest to the pump. Pressure-drop between node 2 and 3 and nodes 3 and 4 are 24.22 and 16.43 percent respectively. This shows that even at no leak condition, pressure drop along the pipeline network can be significantly. This we can confirm to be due to the near pump proximity effect which tends to taper off as the pipeline attains stability further away from the pump.

The pressure profile of the pipeline network with leakage introduced in leak valve 1 is as shown in Figure 5. The figure shows how the pipeline pressure profile changes vis-à-vis when no leak exists on the pipeline network. From the result, even though the leak was only at leak valve 1, reduction in pressure was observed at all the four nodes on the pipeline network with an average of 15 percent pressure reduction in comparison to the pressure profile of the network under no leak condition.

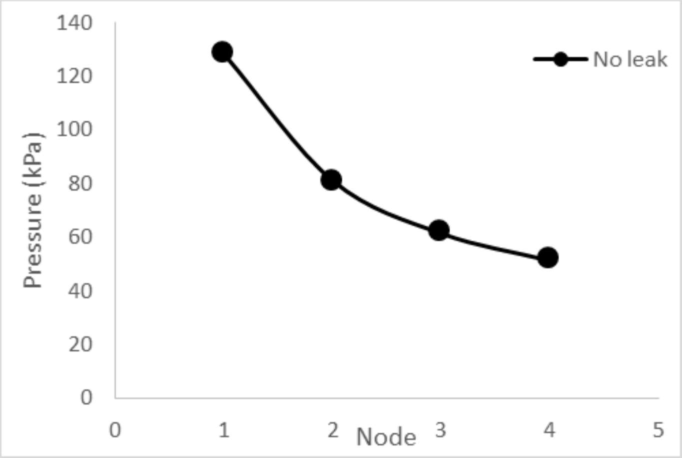

Figure 4: Pressure profile of pipeline network under no leak condition

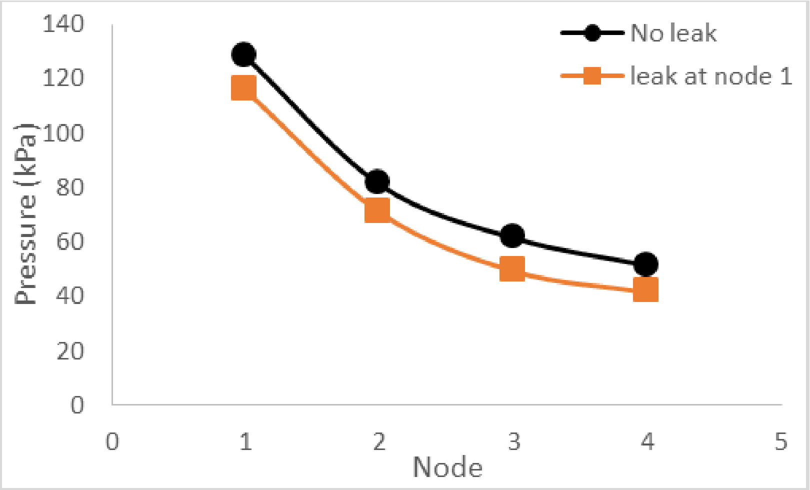

Figure 5: Pressure profile of pipeline network under no leak and at leak at node 1

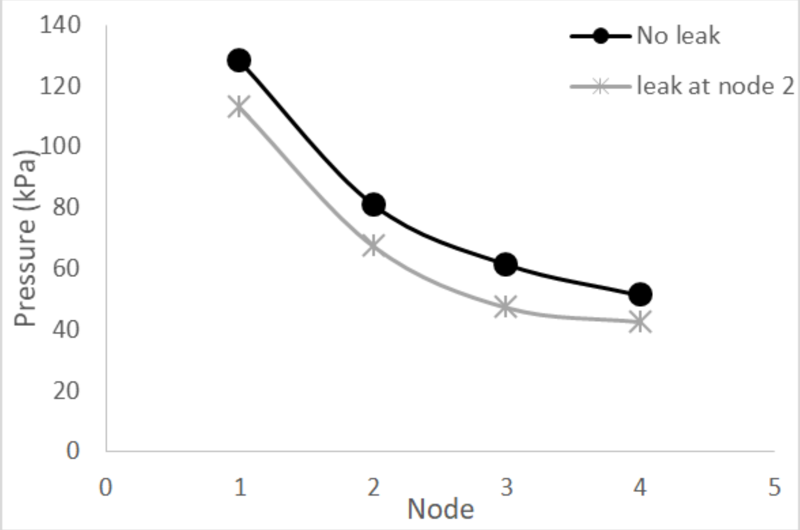

Figure 6: Comparison of pressure profile with no leak and with leak in node 2

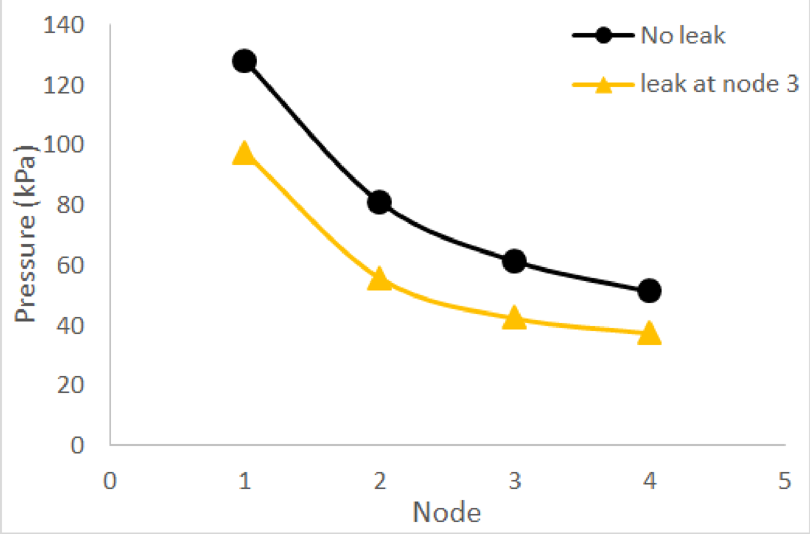

Figure 7: Comparison of pressure profile with no leak and with leak in node 3

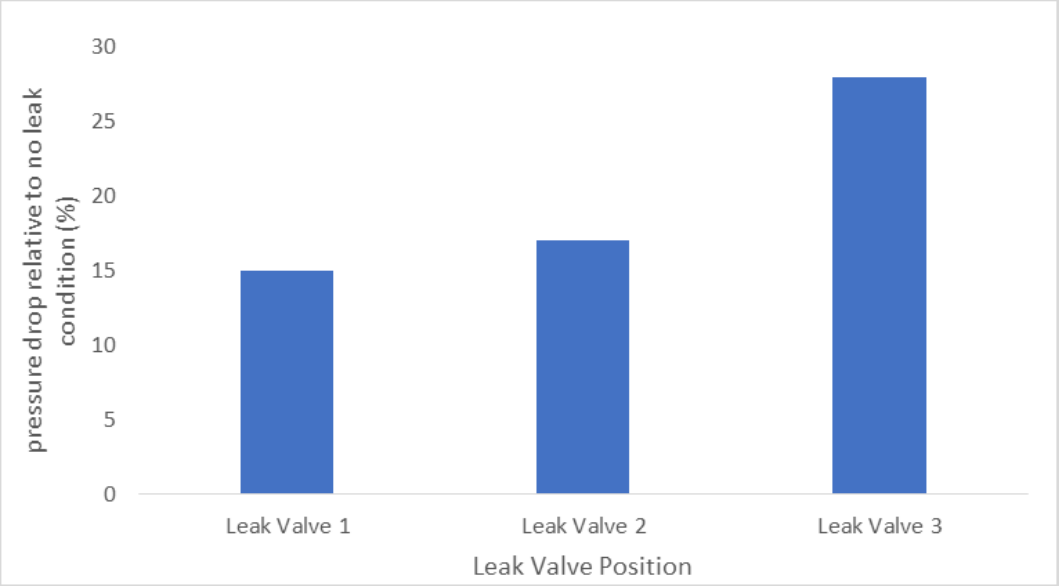

Figure 8: Percentage drop in pressure due to leak position

The result for a similar scenario but with leak created using leak valve 2 and 3 is as shown in Figure 6 and 7 respectively. The average pressure drop due to leak in node 3. The result also indicates that at 28 percent, the pressure drop due to leak 3 was the highest when compared to 17 percent for leak 2 as shown in Figure 8. This can be attributed to two reasons, first the third leak is the closest to the return loop of the pipeline network. Also, this point is the furthest from the pump hence the pressure along the network is deemed to be stabilizing.

Also, from the results obtained in Figure 5, 6, 7 and 8, it is slightly difficult to be specific about the exact leakage point due to the pumping effect of the pump on the pipeline network. However, it can be noted that as the leakage point move further away from the pump where leakages can be easily compensated for by the pressure effect of the pump, the leakage impact becomes more pronounced and can consequently be more easily identified. These results underscore the peculiar challenge of this section of a pipeline network. Hence in analyzing pipeline networks, we have shown that adequate care must be taken to incorporate the effect of the near pump effect in every analysis to avoid reliance on misleading data.

We also examined the impact of multiple leaks. Figure 9 and 10 shows the impact of double leaks positioned at different points on the pipeline.

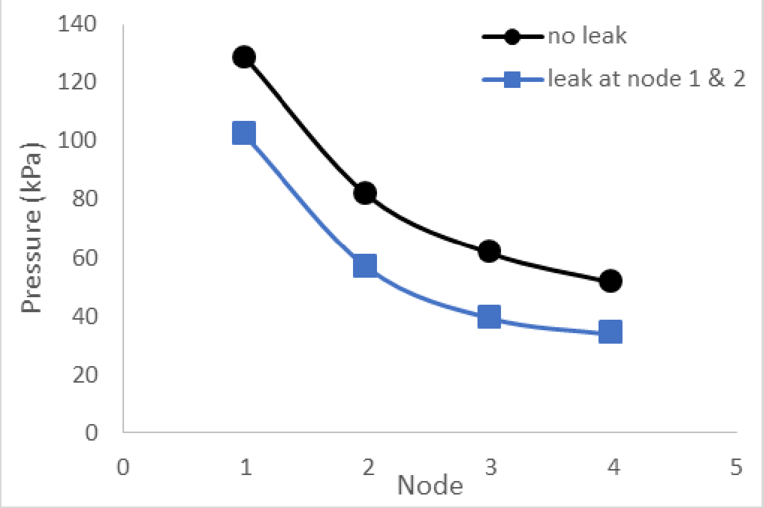

Figure 9: Pressure profile with leak in valve 1 and 2

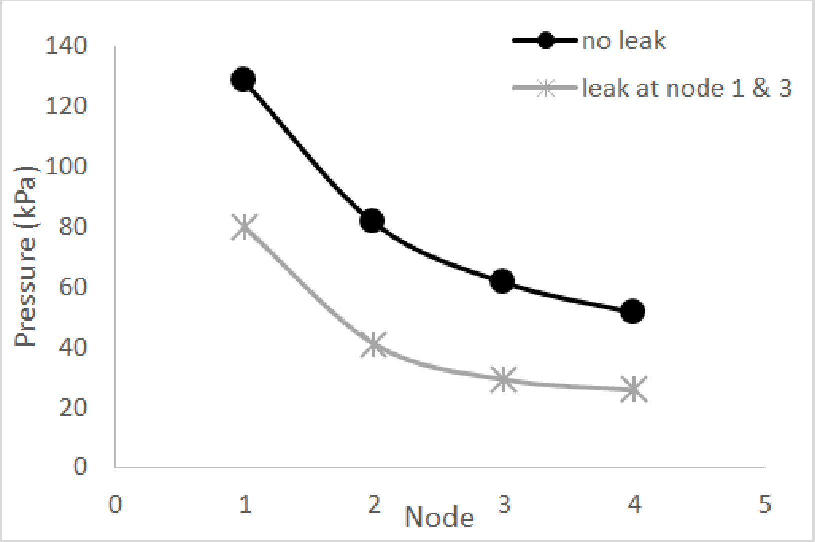

Figure 10: Pressure profile with leak in valve 1 and 3

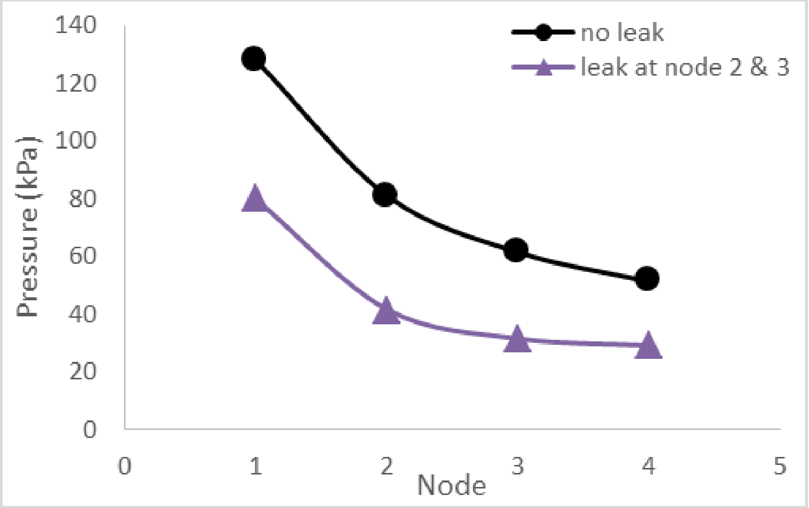

Figure 10: Pressure profile with leak in valve 2 and 3

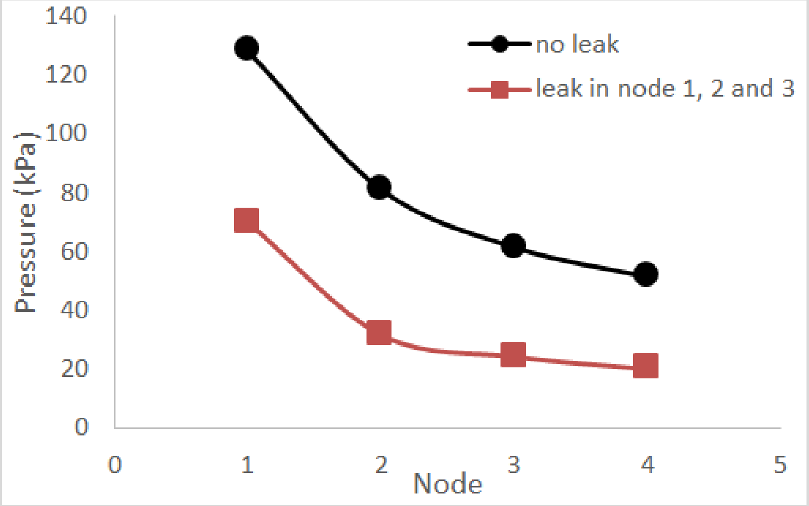

Figure 11: Pressure profile with leak in valve 1, 2 and 3

The result in Figure 9 is the pressure profile with leaks in valve 1 and 2 while Figure 10 profiles the pipeline network with leaks in valve 1 and 3. By comparing the two results. The results shown that leakage at leak valve 3 has the highest impact on the pipeline network at an average of 47 percent. The same trend was observed in Figure 11 and 12. The result in Figure 12 is the network profile with leak in all the three leaks valve which expectedly gave the greatest pressure differential at an average of 57 percent in comparison with the pressure at the excitation point from the pump.

CONCLUSION

In this study, we investigated the impact of near pump or pump proximity effect on close loop pipeline network. The proximity effect is more pronounced on area of around 100 meters of the excitation point which is the location of the pump in the network. These areas of the pipeline network are important because the pressure at this area is greater than any other area of the pipeline due to the pumping action of the pump. This area is also subject to more pressure and stress than any other area.

However, the result shows that leakage may be more difficult in isolate in this area of the pipeline since high pressure from the pump may compensate for any pressure loss. Also, this area of the pipeline is more susceptible to data misinterpretation due to lack of constancy which is usually expected in a pipeline network with no leak. The result shows that pressure in this area of the pipeline can in fact decrease further away from the pipeline due to the lack of stability. In pipeline design, it is important that this area of the pipeline be given specifical consideration to ensure stability and preserve the integrity of logged data. Finally, it is also noted that exclusive pressure readings for leakage detection in near pump environments can only give an approximate result which cannot be sufficiently exact for leak localization task.

It is recommended that machine learning models like neural networks and support vector machine be deployed on collected data to investigate how such models can help to improve both leak detection and localization task on pipeline networks under the influence of near pump pressure loss phenomenon. This is an area of consideration for future extension of this study.

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