STATUS REVIEW ON PIPELINE LEAKS DETECTION AND LOCALIZATION SYSTEMS USING WIRELESS SENSOR NETWORK

Soja, J.S., Thuku, I.T.*, Ibrahim, V.M. and Luka, M.K.

Department of Electrical and Electronics Engineering, Modibbo Adama University, Yola, Adamawa State, Nigeria

*Corresponding email: itthuku@mau.edu.ng

ABSTRACT

In many developing countries, such as Nigeria, crude oil and water are transported via pipelines. However, issues like pipeline bursts, corrosion, aging infrastructure, and theft can lead to leakages, resulting in energy loss, environmental pollution, climate change, and risks to human health. Leak detection and localization in pipelines have become a critical focus of research, with numerous studies conducted to address this challenge. This review paper aims to explore and evaluate the existing methodologies for leak detection and localization in water pipelines, particularly within the context of developing countries like Nigeria, where crude oil and water are often transported through pipelines. More so, this paper examines various techniques used to detect and localize pipeline leaks, including traditional methods, sensor-based technologies, and AI based Machine Learning techniques. The significance of this review is geared toward ongoing efforts to reduce energy loss, prevent environmental pollution, climate change and ease the risks to human health associated with pipeline leakages. Furthermore, the findings provide a valuable foundation for future studies focused on enhancing the accuracy and efficiency of leak detection and localization systems, thereby contributing to the sustainability and safety of pipeline infrastructure.

Keywords: leakage detection system, pipeline, wireless sensor network and localization system

1 INTRODUCTION

A leak detection and localization system are crucial for promptly responding to pipeline failures, ensuring the protection of both the public and the environment. The primary objective of these systems is to help pipeline operators to accurately detect and pinpoint leaks with the necessary precision. The efficient operation of water pipeline is critical for ensuring the reliable supply of clean water to communities. However, pipeline leaks can result in substantial water loss, infrastructure damage, and service disruptions. Pipelines serve as vital lifelines, offering one of the safest and most efficient means of transporting large volumes of fossil fuels, natural gas, water, and other essential hydrocarbon fluids. Crude oil is been conveyed from offshore to onshore, processing plants to domestic and industrial use [1]. Equally, a pipeline is also prone to leaks caused due to several factors like corrosion, aging and theft [2], and is one of the most severe problems which causes wastage of resources and can cause environmental disasters. Pipelines leak detection and localization has become a highly active area of research in recent years, driven by numerous incidents ranging from minor leaks to major failures and its localization [3]. In recent times, most explosions caused by pipeline leaks have killed or injured many people and properties worth millions of naira are lost [4]. More so, millions of gallons have leaked from heavy crude oil pipelines onto land or into the ocean which equally destroy and cause water pollution. Pipeline leaks and blockage usually have damaging effects on the environment, human safety, property, and also lead to financial losses and cleanup expenses. Year in year out, significant quantities of these resources are lost annually and hence a reliable Leak Detection System (LDS) is imperative. Leakage can occur due to fatigue cracks, which result from material fatigue and are often found along longitudinal welds [5]. Additionally, tensile stress can cause stress tears, compromising corrosion protection systems and leading to pipeline corrosion and eventual leakage. Cracks may also form due to hydrogen formation, where atomic hydrogen diffuses into the metal grid of the pipe wall and forms molecular hydrogen, potentially causing pipe failure [4]. Furthermore, manufacturing defects and external forces acting on the pipeline can also contribute to leakage. Examining the causes and impacts of pipeline disasters in Nigeria is essential at the initial stage before detecting leaks and their locations in water pipelines [32]. This is because the extraction, processing, and transportation of petroleum have led to ecosystem disruption, environmental damage, and loss of life in numerous developing countries [30]. This review is both timely and crucial, particularly with the deployment of cutting-edge technology, as it opens up more opportunities for researchers to explore this area of study and develop methods for accurately detecting and localizing water pipeline leakages. It is aimed at identifying the strength and weakness of various leak detection and localization system/techniques. The reminder of this paper is divided into different sections, section two deal with pipeline leak detection techniques while section three covers pipeline leak localization system and finally section four briefly highlights the basics of fluid flow in water pipeline [6].

2 PIPELINE LEAK DETECTION TECHNIQUES

Leak detection in pipelines can be classified into continuous and non-continuous approach [25]. The continuous based approach can be subdivided into externally based and internally/computational based methods. The non-continuous approach entails visual and inspection approach. The externally based leak detection methods operate on the bases of non-algorithmic principle of physical detection of an escaping commodity using dedicated external sensors. The internally/computational leak detection methods operate based on system model or algorithmic principle that monitors the flow of parameters in real-time. Visual or inspection methods do not monitor the flow parameters in real-time instead it involves the use of helicopter, trained dogs and personnel for physical inspection. The helicopter flies very low along the pipeline detecting any outflow of gas using laser, infrared cameras and leak sniffers. The laser is configured by setting it to the absorption wavelength of the medium to be detected. Leak can be detected whenever the hits the medium, part of the laser energy will be absorbed and the absorbed part of the energy is measured to effectively detect the leak. They are scheduled at regular intervals to be carried out by humans or trained dogs for visual inspection [7]. Leak detection and localization methods for pipelines fall into three main categories namely, acoustic methods, real-time transient models, the negative pressure wave method, and optical fiber techniques. Some specific approaches within these categories are flow rate monitoring, pressure point analysis, distributed fiber optic sensing, acoustic sensing, real-time transient modeling, model simulation, infrared cameras, and radar systems. An internal leak detection system utilizes point-to-point sensors to monitor liquid flow rates. It also employs mathematical and statistical computations to track flow rates, pressures, temperatures, and other product characteristics [8]. This method is effective for identifying leaks; however, one of its drawbacks it has a limited sensitivity. Leaks often take longer time to be detected, and small leaks may likely go unnoticed [9]. An externally based leak detection system utilizes acoustic sensors to identify changes in sound patterns associated with pipeline leaks. When a leak occurs, the escaping fluid generates distinct sound frequencies that differ from background noise. These sensors are strategically placed along the pipeline route to continuously monitor variations. When a potential leak is detected, an alert is triggered, enabling prompt investigation and necessary action [8]. Other externally base leak detection system includes fiber optic sensing cable, vapor sensing tube, and liquid sensing tube. On the other hand, visual inspection method involves the use of trained personnel and trained dogs to visually inspect leaks or damages along pipeline [10]. They search for any physical and strange things such as stains, discoloration, vegetation damage, or any unusual fluids and odors that may be suspected as leakage. This method is very difficult and involves human efforts and it also provides quick response and allows for immediate visual identification of possible issues [5].

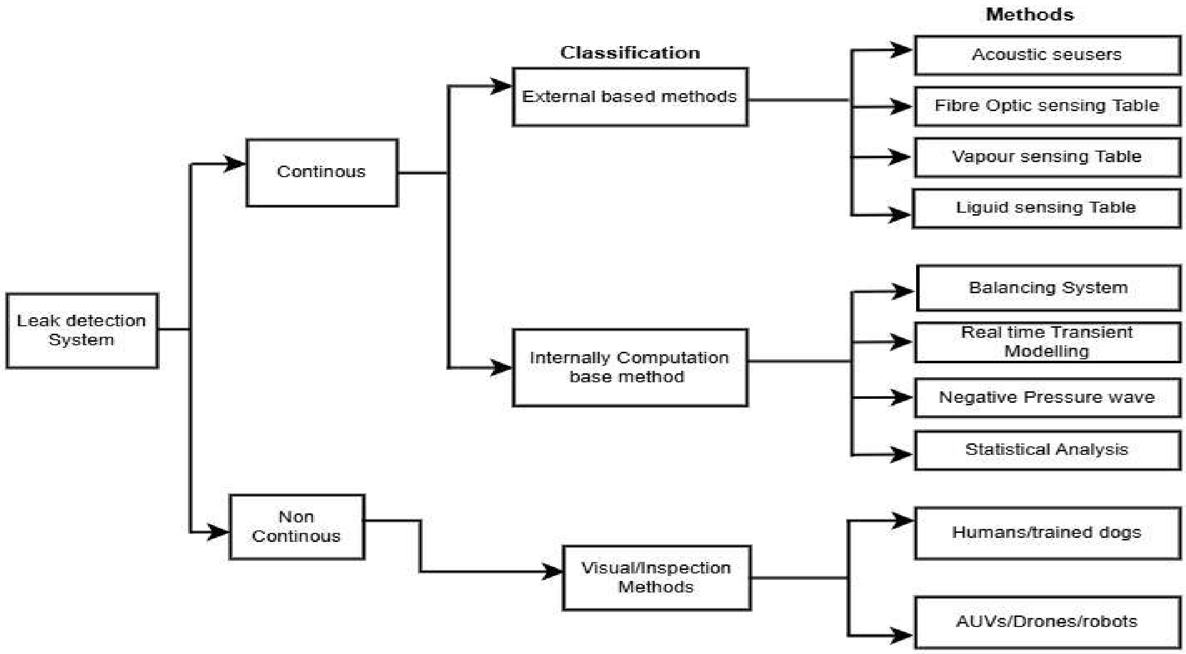

Figure 1. Classification of pipeline leak detection approach [4]

Table 1. Strength and weakness of some selected Leak Detection models

Models	Approach	Application	Advantages	Disadvantages
Negative Pressure Wave	Pressure waves generated by leaks are propagated as wave and recorded using pressure transducers	Transporting networks and medium pressure networks	Requires no mathematical model and easy to implement	Not applicable on long-range pipelines with a tiny leak
Pressure point Analysis	Detect leak when mean value of the pressure reduces under predefined threshold	Transporting networks, medium pressure networks	Easy to maintain and can detect small Leaks	Application is slim and difficult to localize leak points
Mass/Volume Balance	When there is leak, Systematic deviation is presented using mass balance equation	Transporting networks, medium pressure networks	A very easy principle	It is always Sensitive to any disturbances which leads to high false alarms
Distributed temperature sensing	leaks are identified when temperature change which is detected by fiber optic cables	Transporting networks, distribution networks	Response very fast with high accuracy for leak location	Difficult to implement and cannot detect multiple leaks
Probabilistic based method	This approach is used for leak detection and localization	distribution networks	Small Sample data is required.	cannot identify multiple leaks
Real time transient model	Creating simulation atmosphere to mimic conduct of pipeline using computational algorithms	Distributed network	It has high accuracy of monitoring internal leaks	Cannot detect exact leaks location

3 PIPELINE LEAK LOCALIZATION SYSTEMS

Researchers have long faced challenges in accurately locating leaks in pipelines. The study of leak detection and localization began with the groundbreaking work of Pudar and Liggett in 1992, where they framed the problem of leak detection and localization as a least-squares inverse problem. In their approach, the equivalent outlet areas of potential leaks are treated as unknown variables, with the solution obtained by minimizing the discrepancy between measured and calculated pressure heads. This problem formulation highlights the importance of both detecting and localizing leaks, which requires monitoring multiple points within the pipeline system, while assuming that certain network parameters are known [11]. In a research conducted by [12] the researchers proposed utilizing acoustic sensors and a Data Acquisition (DAQ) system, combined with appropriate signal processing software, to detect and locate leaks in pipelines. Their method relies on estimating the time delay between signals captured by two adjacent sensors along the pipeline. Additionally, Cross-Correlation (CC) technique is employed, along with effective filtering of acoustic signals before correlation to enhance the reliability of leak position estimation. [13] Proposed a model-based leakage localization method for distribution water networks. The approach involves deploying flow and pressure sensors at the inlets of District Meter Areas (DMAs), supplemented by a limited number of pressure sensors within each DMA. To ensure optimal sensor placement and effective coverage, a Genetic Algorithm-based optimization method is utilized. This strategy integrates a direct modeling approach (simulation) to enhance the identification of leak locations. There is various leak localization approach aimed at identifying the location of leaks in water pipeline. Acoustic-based leak localization systems utilize acoustic sensors to capture the noise produced by leaks and apply signal processing techniques to determine their location. The noise generated by a pipeline leak results from vibrations, turbulent flow, and pressure fluctuations within the pipe [14]. In the case of pressure-based leak localization systems, they are used for detecting and localizing leaks in water, gas, and oil pipelines by monitoring pressure variation along pipeline. This method involves the use of mathematical models, sensor networks, and AI techniques to estimate leak locations. This technique also involves the use of Inverse Transient Analysis (ITA) Method, pressure drop analysis and time difference of arrival depending on the methods adopted by researchers [15, 16, 17]. Flow-based leak localization systems identify leaks by detecting abnormal flow variations within a pipeline network. These systems rely entirely on flow sensors to measure the velocity and volume of fluid at different points. By comparing inflow and outflow, any discrepancies indicate a potential leak. There are other techniques that are used for leak detection, including the Mass Balance Method**,** Negative Pressure Wave (NPW) Method**, and** Machine Learning-Based Flow Anomaly Detection [18, 19]. More so, model-based leak localization systems use mathematical models and simulations to detect and identify leaks in pipeline networks [20]. This model depends on hydraulic, statistical, and AI-driven models to analyze deviations in pressure, flow, or acoustic signals. Leaks can be known by comparing real-time sensor data with expected system behavior [21]. This model-based leak localization system can be categorized into three main types: Hydraulic Model-Based Leak Detection, Data-Driven Model-Based Detection, and Inverse Problem Formulation [22, 26, 27, 28], however, these systems have some drawbacks which include high computational power especially for large pipeline networks, highly sensitive to noise, which can affect accuracy. Large datasets are needed for training AI-based models and complex computations make real-time processing challenging. Thermal and infrared leak detection operates by identifying temperature changes caused by evaporation, pressure drops, or fluid expansion**.** Infrared cameras capture heat variations between the leaking substance and its surroundings, enabling precise leak localization. The AI-based leak detection and localization technique successfully achieved its objective by analyzing sensor data from pressure, flow, and acoustic measurements to identify anomalies and accurately predict leak locations. The process begins with data collection from sensors, followed by preprocessing to refine the collected data. Key features such as pressure drops and flow rate variations are then extracted. Finally, this information is used for training the AI model, enabling effective leak prediction and localization. Figure 2 shows leak localization approaches.

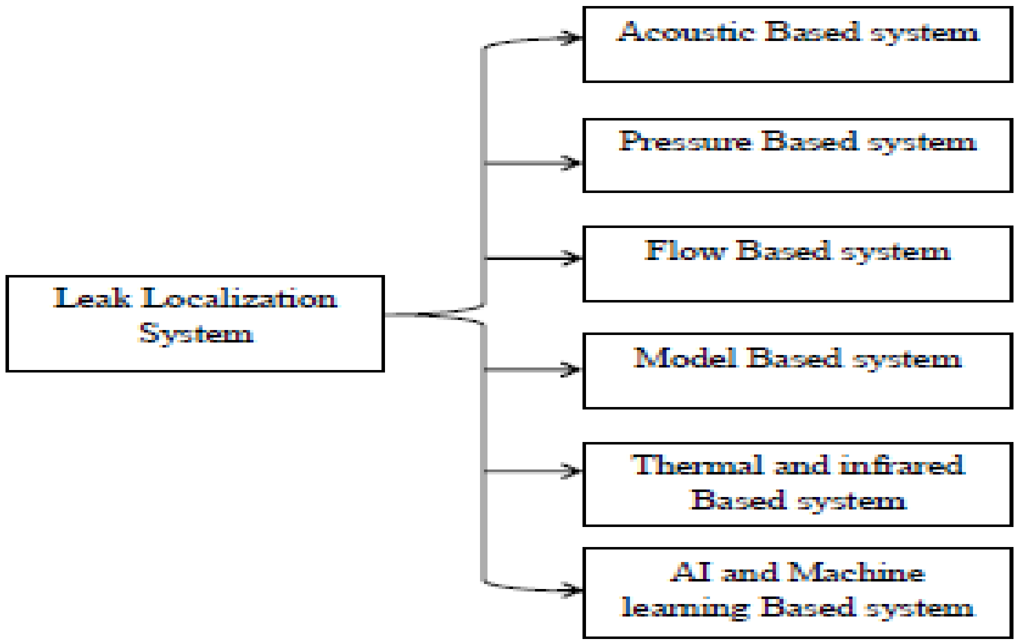

Figure 2. Leak localization approaches

4 FLUID FLOW IN PIPELINE

Understanding fluid dynamics in pipelines is essential for minimizing energy losses and addressing critical issues such as leakages, blockages, and their localization in water pipelines [31]. Fluid flow in pipelines can be either laminar or turbulent**,** depending on key parameters [23]. Laminar flow occurs when the Reynolds number (Re) is less than 2,000 and is characterized by smooth, orderly layers of fluid moving parallel to the pipeline walls. In contrast, turbulent flow features irregular and chaotic flow patterns and occurs when Re exceeds 4,000 [24]. According to [29], fluid velocity in a pipe changes from *zero* at the surface because of the no-slip condition to a maximum at the center of the pipe. Several fundamental equations govern fluid flow, including the continuity equation (conservation of mass), Bernoulli's equation (energy conservation), and the Navier-Stokes equations (momentum conservation) [31]. Various factors influence fluid flow in pipelines, such as pipe diameter and length, fluid properties, flow rate, and velocity. A deep understanding of fluid flow in pipelines is crucial for several industries. In oil and gas, it ensures the efficient transportation of natural gas over long distances. In water distribution networks, it plays a vital role in supplying water to urban and rural areas. The chemical industry relies on fluid flow for transporting chemicals between manufacturing plants, while HVAC systems use controlled fluid dynamics to regulate water and air flow for heating and cooling applications [28].

5 CONCLUSIONS

This review is particularly relevant as leak detection and localization systems utilizing wireless sensor networks (WSNs) to provide an efficient and scalable solution for pipeline monitoring, enabling early leak detection and its localization. However, challenges such as sensor placement optimization, power management, scalability, complexity and data processing must be addressed to enhance reliability and efficiency. Advancements in AI, machine learning, and network optimization improves the effectiveness of WSN-based pipeline monitoring and operations. This review is especially valuable for researchers looking to conduct rigorous studies in this field by adopting AI techniques such as machine learning and deep learning alongside wireless sensor deployments to achieve more accurate results.

REFERENCES

1. Fan, H., Tariq, S. and Zayed, T. (2022). Acoustic leak detection approaches for water pipelines. *Automation in Construction*, vol. 138, pp. 104-226.
2. Boaz, L., Kaijage, S. and Sinde, R. (2014). An overview of pipeline leak detection and location systems. In *Proceedings of the 2nd Pan African International Conference on Science, Computing and Telecommunications*, pp. 133-137.
3. Wang, W. and Gao, Y. (2023). Pipeline leak detection method based on acoustic-pressure information fusion. *Measurement*, vol. 212, pp. 112691.
4. Korlapati, N.V.S., Khan, F., Noor, Q., Mirza, S. and Vaddiraju, S. (2022). Review and analysis of pipeline leak detection methods. *Journal of Pipeline Science and Engineering*, pp. 100074.
5. Geiger, G., Vogt, D. and Tetzner, R. (2006). State-of-the-art in leak detection and localization. *Oil Gas European Magazine*, vol. 32, no. 4, 193.
6. Swain, A., Abdellatif, E., Mousa, A. and Pong, P.W. (2022). Sensor technologies for transmission and distribution systems: a review of the latest developments. *Energies*, vol. 15, no. 19, pp. 7339.
7. Zhang, J., Hoffman, A., Kane, A. and Lewis, J. (2014). Development of pipeline leak detection technologies. In *International Pipeline Conference American Society of Mechanical Engineers*, vol. 46100, no. V001T09A030, 31p.
8. El-Shiekh, T.M. (2010). Leak detection methods in transmission pipelines. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 32, no. 8, pp. 715-726.
9. Fiedler, J. (2014). An overview of pipeline leak detection technologies. *American School of Gas Measurement Technology (ASGMT), Peabody, MA, US*, 38p.
10. Ho, M., El-Borgi, S., Patil, D. and Song, G. (2020). Inspection and monitoring systems subsea pipelines: A review paper. *Structural Health Monitoring*, vol. 19, no. 2, pp. 606-645.
11. Akyildiz, I.F. and Vuran, M.C. (2010). Wireless sensor networks. *John Wiley & Sons*, pp. 43-49.
12. Kemler, E. (1933). A study of the data on the flow of fluids in pipes. *Transactions of the American Society of Mechanical Engineers*, vol. 55, no. 3, pp. 7-22.
13. Deville, M.O., Fischer, P.F., Mund, E.H. and Gartling, D.K. (2003). High-order methods for incompressible fluid flow. *Appl. Mech. Rev*., vol. 56, no. 3, pp. B43-B43.
14. Farshad, F., Rieke, H. and Garber, J. (2001). New developments in surface roughness measurements, characterization, and modeling fluid flow in pipe. *Journal of Petroleum Science and Engineering*, vol. 29, no. 2, pp. 139-150.
15. Klainerman, S. and Majda, A. (1982). Compressible and incompressible fluids. *Communications in Pure Applied Mathematics*, vol. 35, pp. 629-651.
16. Thorley, A.R.D. and Tiley, C.H. (1987). Unsteady and transient flow of compressible fluids in pipelines—A review of theoretical and some experimental studies. *International journal of heat and fluid flow*, vol. 8, no. 1, pp. 3-15.
17. Sophocleous, S., Savić, D. and Kapelan, Z. (2019). Leak localization in a real water distribution network based on search-space reduction. *Journal of Water Resources Planning and Management*, vol. 145, no. 7, pp. 04019024.
18. Kousiopoulos, G.P., Papastavrou, G.N., Karagiorgos, N., Nikolaidis, S., Efstathiadis, T. and Kalfas, A. (2019). Pipeline leak localization techniques. In *2019 Panhellenic Conference on Electronics & Telecommunications*, pp. 1-4.

19. Meseguer, J., Mirats-Tur, J.M., Cembrano, G. and Puig, V. (2015). Model-based monitoring techniques for leakage localization in distribution water networks. *Procedia Engineering*, vol. 119, pp. 1399-1408.

20. Feng, C., Zhao, J., Ran, Q., Qu, M. and Guo, Z. (2024). Acoustic-based approach for micro-leakage detection and localization in water supply pipelines. *Environmental Science: Water Research & Technology*, vol. 10, no. 8, pp. 1881-1889.

21. Sun, C., Parellada, B., Puig, V. and Cembrano, G. (2019). Leak localization in water distribution networks using pressure and data-driven classifier approach. *Water*, vol. 12, no. 1, pp. 1-54.

22. Boaz, L., Kaijage, S. and Sinde, R. (2014). An overview of pipeline leak detection and location systems. In *Proceedings of the 2nd Pan African International Conference on Science, Computing and Telecommunications*, pp. 133-137.

23. Marzola, I., Alvisi, S. and Franchini, M. (2022). A comparison of model-based methods for leakage localization in water distribution systems. *Water Resources Management*, vol. 36, no. 14, pp. 5711-5727.

24 Vanijjirattikhan, R., Khomsay, S., Kitbutrawat, N., Khomsay, K., Supakchukul, U., Udomsuk, S. and Anusart, K. (2022). AI-based acoustic leak detection in water distribution systems. *Results in Engineering*, vol. 15, pp. 100557.

25. Chis, T. (2009). Pipeline leak detection techniques. *arXiv preprint arXiv:0903*, 4283p.

26. Romero-Ben, L., Alves, D., Blesa, J., Cembrano, G., Puig, V. and Duviella, E. (2022). Leak localization in water distribution networks using data-driven and model-based approaches. *Journal of Water Resources Planning and Management,* vol. 148, no. 5, pp. 04022016.

27. Tetzner, R. (2003). Model-based pipeline leak detection and localization. *3R International. Rohre. Rohleitungsbau. Rohrleitungssysteme*, 42p.

28. Romero-Ben, L., Blesa, J., Cembrano, G. and Puig, V. (2023). A comparison between model-based and data-driven leak localization methods. *IFAC-PapersOnLine*, vol. *56*, no. 2, pp. 737-742.

29 Sam Ani, H M. and Khayatzadeh, A. (2002). Transient flow in pipe networks. *Journal of Hydraulic Research*, vol. 40, no. 5, pp. 637-644.

30. Stephenson, D.J. (1981). Pipeline design for water engineers. *Elsevier*, vol. 15, pp. 67.

31. Raman, R.K., Dewang, Y. and Raghuwanshi, J. (2018). A review on applications of computational fluid dynamics. *Int. Jour. LNCT*, vol. 2, no. 6, pp. 137-143.

32. Johnson, F.I., Laing, R., Bjeirmi, B. and Leon, M. (2022). Examining the causes and impacts of pipeline disasters in Nigeria. *AIMS Environmental Science*, vol. 9, no. 5, pp. 636-657.