 

# A Review of Leak Detection Systems for Natural Gas Pipelines and Facilities

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**Abstract**
Pipelines facilities, used for the transportation of natural gas in large quantities to homes and industries, remain the best economic, most reliable and safest mode of transport of energy. Despite these numerous advantages, gas pipelines have been enmeshed in various accidents and thefts, nonetheless this could be reduced if properly maintained and pipelines can last indefinitely without leaks. Pipelines are susceptible to leakages and rupture accidents as a result of age, corrosion, material defects, operational errors or other reasons. Pipeline failures may be caused intentionally (e.g. vandalism) or unintentionally (e.g. device/material failure and corrosion), which may result into irreversible damages such as financial losses, human casualties, ecological disaster and extreme environmental pollution. Leakages in natural gas facilities and installations require three vital aspects, namely: Gas Leakage Prevention, Gas Leakage Detection and Gas Leakage Mitigation. Many Gas Leak Detection methods are used for pipeline integrity management and especially for minimizing gas leakage. The performance of these methods depends on the approaches, operational conditions and pipeline networks. Also, there are some essential requirements and guidelines which must be met before we can consider any leak detection system suitable for production solutions, including sensitivity, reliability, accuracy and robustness. The attempt of this study is to carry out a critical review of these models, to ascertain the best model(s) applicable to natural gas leak detection.
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## 1. Introduction
Pipeline facilities, used for the transportation of natural gas in large quantities to homes and industries, remains the best economic, most reliable and safest mode of transport of energy, with recent rapid increasing energy consumption and its attendant significant growth in natural gas industry (Shan et al, 2017). There are a total of slightly less than 2,175,000miles (3,750,000km) of pipeline in 120countries of the world, which have greatly assisted to fulfill high demands of safety, reliability and efficiency. Despite being the most economical, most reliable and safest means of transporting natural gas compared to other methods of transportation possibilities, gas pipelines have been enmeshed in various accidents and thefts, nonetheless but this could be reduced if properly maintained and pipelines can last indefinitely without leaks. Pipelines are susceptible to leakages and rupture accidents as a result of corrosion, material defects, operational errors or other reasons, which are further aggravated by the long distance covered, coupled with its high energy and flammable nature. Pipeline failures may be caused intentionally (e.g. vandalism) or unintentionally (e.g. device/material failure and corrosion), which may result into irreversible damages such as financial losses, human casualties, ecological disaster and extreme environmental pollution, most especially if the leakage is not detected promptly (Adegboye, 2019). Human errors and excavating machinery account for no less than 76.2% of the damaged pipelines, leading to gas leakage, with the flammable gas inducing explosion upon reaching a concentration of 5% in the air (Lu *et al*, 2014).

Thus, gas leak detection is done to minimize the damaging effects of leaks and spills, but despite the avalanche of advanced leak detection technology, the human role in pipeline monitoring is still very important because remote monitoring does not always detect every small leak or slow leaks, but responsible neighbors need to be aware of the signs of a pipeline release. It should be noted that Leak Detection Systems do not and cannot eliminate leaks but it can potentially reduce its impact through earlier detection and remedial action (CAPP, 2018). Effective leak detection systems can help minimize damage to people, the environment, and the company image as well as the high costs for repair, renovation, indemnity, breakdowns and the lost value of the liquid or gas that has been released (Fiedler, 2016). Proper pipeline maintenance, effective pipeline monitoring for timely detection of leakage and even leak prediction remain the best solution, as early leak detection permits rapid responses to stop leakage (Adegboye, 2019), while prompt identification of pipeline leaks also improves safety and protects the natural environment (Sibray & Hallum, 2016). Whereas inspectors walking the length of pipelines and visually inspecting for evidence of leaks was enough, it is no longer possible today with many cases inhibiting physical access due to distances (Fielder, 2016). Leak Detection Systems (LDS) are aimed at helping pipeline controllers detect and localize leaks, thus they incorporate alarms and display other related data which assist in decision-making. They can also enhance productivity and system reliability which reduces downtime and inspection time.

**2. Review of Related Literatures**

Appah *et al* (2021) did a comprehensive assessment of the existing techniques to detect and quantify gas leaks in natural gas infrastructure based on the amount of leak detected compared to amount of gas produced from such facilities. They found out that the uncertainties associated with efficient quantification of natural gas leak rates demonstrate the need for innovative approaches or processes to identify and quantify leak rates from gas infrastructure and called for immediate actions. But the work could not ascertain which method was the right and best leak detection system, suggesting instead that each application depends on the desired results, cost of installation, operation, maintenance and installation conditions. Adegboye *et al* (2019) discussed pipeline leakage detection technologies and summarized the state-of-the-art achievements, together with their strengths and weaknesses. They also carried out comparative performance analysis needed to provide a guide in determining which leak detection method was appropriate for particular operating settings. However, they did not consider the use and the design of a real-time intelligent leak detection and localisation system for subsea pipeline networks and neither did they consider the effect of environmental factors such as hydrodynamic forces due to oblique wave and current loading on subsea pipelines which requires further research study. CAPP (2018) used best management practice with the intention to guide operators of upstream pipelines in the selection, operation and maintenance of pipeline leak detection programs developed to address leak detection as part of upstream operators' focus on performance improvement through companies' pipeline integrity programs. This resulted into quicker leak detection, reduced the environmental impacts from leaks and improved pipeline performance, particularly in high-risk areas. But the report disclosed that the impact of any changes on pipeline operators' leak detection management programs must be assessed if and when changes are implemented and appropriate modifications made to the leak detection. Baroudi *et al* (2019) discussed extensively various leak detection systems and data fusion approaches that are applicable to pipeline monitoring, with a thorough analysis, comparison and detailed classification. They concluded that each leak detection system was a unique system designed based on the pipeline for which it is developed and its choice should be based on a fit-for-purpose approach and on the operating parameters (pipeline size, length, instrumentation design). But they called for thorough review of available historical data regarding pipe performance and failure to give greater insight while suggesting an increase in accuracy to minimize false alarms.

Fiedler (2016) provided an extensive background study of the working principles of various pipeline leak detection methods, detailing the historical development, reasons for monitoring for leaks, legal requirements and regulations. However, the paper failed to decide on the right or best leak detection system, rather requesting for further investigation. Wang (2015) came up with a novel and interdisciplinary concept, making full use of the computer vision advances to automatically classify natural gas leak. They performed sensitivity analysis in order to examine the effect of feature selection, training and testing data size, noise threshold for optical flow calculation, number of frames which histogram of gradients performs on. But the paper fall short of requesting for the collection of sufficient data in order to develop more robust detection algorithm of the plume and then used a regression model to predict the leak size through the use of convolutional neural network. In their study, Scott and Barrufet (2003) undertook an examination of various pipeline leak detection technology, analysing their advantages and disadvantages and possible application in deepwater, subsea and arctic developments. They also investigated how current methods might be applied within modern oil and gas development strategies. However, they reported that large-scale experiments were required for multiphase leak detection, there was need to investigate distributed pressure and temperature arrays to extend capability of pressure loss detection methods. Also, the combination of continuous and batch sampling needed to be investigated for reducing the time to detect a leak. In their extensive research. Wang *et al* (2001) surveyed the various leak detection methods, highlighted the attendant advantages and disadvantages of each method and emphasized the selection of the appropriate solutions for the different pipeline systems. They also described recent research on inverse transient leak detection techniques that are currently being carried out with special focus on the inverse transient method and considered this in detail. However, they called for extension of application to other transient based leak detection methods including transient reflection methods, transient damping and transient frequency analysis to improve response time, accuracy of leak detection and application to real pipeline networks be done in its infancy. El-Shiekh (2010) provided the proper methodology to facilitate the choice of leak-detection system, dealt with external methods and with some internal methods based on flow and pressure measurements in the pipeline. However, they could not conclude on the best method but rather called for more detailed study of leak detection and leak localization in transmission pipelines. Sivathanu (1991) carried out a review of the current status of the technology for leak detection from the natural gas pipelines detailing the various leak detection methods. Though he emphasized on the optical methods used for natural gas leak detection, but he could not conclude on a single technique to be identified as the industry standard due to their various limitations.

 

## 3. Leak Detection Systems

There are several pipeline leak detection methods developed using different working principles and approaches to detect natural gas pipeline leaks, ranging from manual inspection using trained dogs to advanced satellite based hyper-spectral imaging. The application of leak detection system to a particular pipeline will depend on environmental issues, regulatory imperatives and operating company loss prevention and safety policy rather than pipe size or configuration (Stafford & Williams, 1996). Some of the existing leakage detection methods are: acoustic emission, fibre optic sensor, ground penetration radar, negative pressure wave, pressure point analysis, dynamic modelling, vapour sampling, infrared thermography, digital signal processing and mass-volume balance. Many leak detection methods are employed in the oil and gas industry for pipeline integrity management and especially for minimizing gas leakage during its transportation to users. The performance of these pipeline leakage detection methods depend on the approaches, operational conditions and pipeline networks. Also, there are some essential requirements and guidelines which must be met before we can consider any leak detection system suitable for production solutions. A good Leak detection system must have minimum detectable leak rate and time to detect a leak (sensitivity), it must be able to avoid false alarms (reliability), it must have the ability to calculate leak and locate leak exactly and promptly (accuracy) and it must be able to detect the failure and at least continue to work (robustness). In addition, leak localisation and estimation of the leakage rate are also important as they will facilitate leakage containment and maintenance at an early stage to avoid serious damage to the environment, facilities and personnel. The determination of the most effective technique for mitigating gas leakage during transportation cannot be over-emphasized.

In this paper, we consider classifying Leak Detection System into Continuous and Non-continuous systems, as depicted in the following figure (figure 1), with detailed description and explanation presented in the table thereunder (tables 1-3). Continuous Monitoring Systems involve the inspection of pipelines round the clock and can be divided into external and internal based systems: In Continuous External systems, local sensors are used to detect pipe leaks and pipe abnormalities and it requires some form of physical contact between the sensor probes and the monitoring facility, these systems are highly sensitive to leaks and can accurately locate leak but are generally expensive and are used only in short pipeline segments or in sensitive locations. In Continuous Internal systems, internal fluid measurement instruments are used to monitor operational and hydraulic parameters associated with fluid flow in pipelines such as flow, pressure and temperature, which are determined either manually by pipeline controllers or based on sophisticated algorithms and hydraulic models. A difference between the measured and predicted operational parameters indicates a leak. Internal systems generally do not require the installation of extensive hardware throughout the pipeline. Continuous internal systems include Pressure point analysis, Mass or volume balance methods, Statistical systems, Real Time Transient Model (RTTM) based systems and Extended-RTTM (E-RTTM) based systems. Non-Continuous Monitoring Systems are the traditional processes of leak detection and they include inspection by helicopter, smart pigging, tracking dogs, trained or experience personnel, soil monitoring, remotely operated vehicles, autonomous underwater vehicles, gas sampling method and flow monitoring devices.

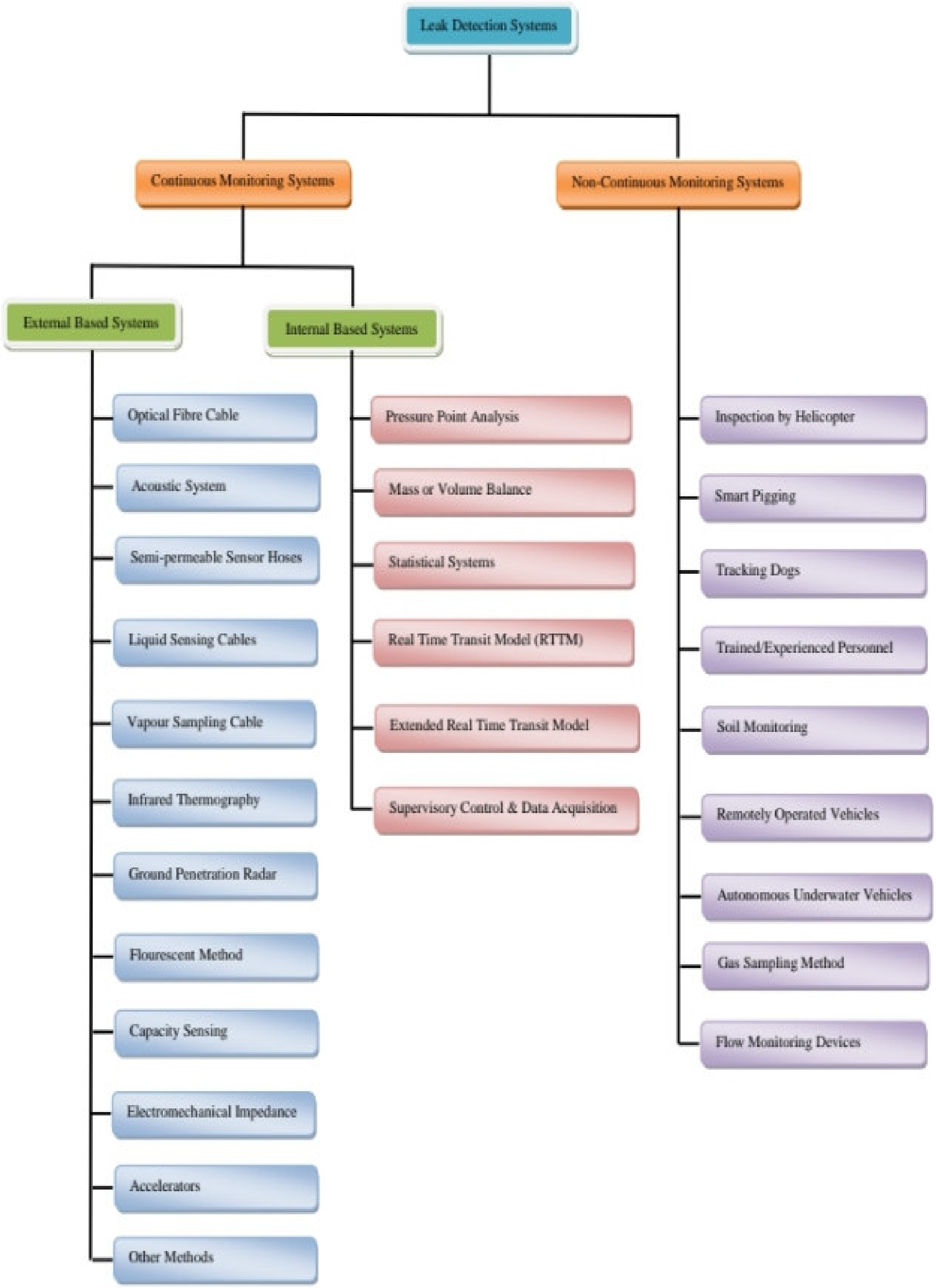


*Figure 1: Classification of Leak Detection Systems*

*Table 1: Continuous External Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 1 | Fiber Optic Cable | Installed along pipe length, with transmission characteristics changing when in contact with liquid. Sound generated and picked up by specially designed hydrophone. Signals are detected, analyzed and evaluated to give leak location. | - Ability to detect small leak<br>- Non-metallic in nature<br>- Monitoring of long pipelines<br>- Insensitivity to electromagnetic interference<br>- Can act both as sensor and data transmission medium | - Limited commercial use; Short lifespan<br>- Inability to estimate leakage rates<br>- Challenge over large/complex network<br>- High implementation cost<br>- Non-applicable for cathodic protected pipelines or existing buried pipelines.<br>- Sensitive to random/environment noise |
| 2 | Acoustic Systems | Sensors mounted on pipeline for leaks detection through measurement of noise or vibration generated by sudden drop in pressure. A noise profile is created, with deviations treated as leak alarm | - Convenience of installation<br>- Suitability for early detection<br>- Easily ported to various pipe sizes<br>- Cost-effectiveness<br>- Non-interference with operations<br>- No shutdown for installation | - Large number of sensors required<br>- High cost<br>- Proneness to false alarm<br>- Inability to detect small leaks<br>- Sensitive to random and environmental noise and prone to false alarms |
| 3 | Semi-permeable Sensor Hoses | Installed along pipeline, leak makes medium comes out into hose. Test gas is injected into hose in a timed cycle. Difference between arrival of medium out of pipeline and that of test gas is used to derive leak size. | - Excellent ability to detect small leaks<br>- Superlative performance for detecting leaks in multiphase flow<br>- Ability to resist significant hydrostatic pressure | - Delay in response time thus a complementary method required with other leakage detection method to obtain an acceptable response time |
| 4 | Liquid Sensing Cables | Sensing cables laid throughout pipeline, which swell in volume or change electrical properties (impedance, electrical resistance, dielectric constant), when in contact with leaking fluids to detect leak | - Used as a distributed sensor<br>- It is non-metallic in nature<br>- System could be used for arctic conditions | - Not applicable to deepwater/offshore<br>- Not applicable to multiphase flow leak<br>- Cable must be air-dried after exposure<br>- Sensor may interfere with the working of pipeline cathodic protection |

*Table 1: Continuous External Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 5 | Vapour Sampling Tubes | When a leak occurs, the leaked material diffuses into the tube and generates an accumulated signal indicating hydrocarbon flit in the tube environment. Leak location is the peak arrival time at the detector compared with the arrival time of the test gas injected in sensor | - Independent of pressure/volume monitoring/flow balance<br>- Sensor can withstand significant hydrostatic pressure<br>- Require not much maintenance<br>- Can detect small leaks which are not detectable by conventional methods | - Requires higher capital investment<br>- Slow response time<br>- Designed for low level leak detection<br>- High cost of leak detection<br>- May not be very effective for deepwater, as the gas can be soluble at that depth. |
| 6 | Infrared Thermography | Detect temperature changes in pipeline environment using infrared cameras in real-time. It is a contactless and non-invasive condition and distributed measurement monitoring tool. | - Efficient transmission of the scan objects into a visualisation form<br>- Fast response time<br>- Ease of use<br>- No experience or training needed<br>- Suitable for all pipeline sizes | - Very expensive cost<br>- Quantifying a leak orifice of less than 1.0 mm is challenging<br>- May observe a significant section of pipeline from an elevated location<br>- Sensitivity is based on volume |
| 7 | Ground Penetration Radar | Uses electromagnetic wave propagation and scattering techniques to detect alterations in magnetic and electrical properties of soil in the pipeline surrounding. | - Timely detection of leakage<br>- Reliability and comprehensive leak information. | - Not applicable for long pipeline<br>- Effectiveness may reduce for buried pipelines based on depth of pipe and use of covering media such as concrete<br>- It is costly<br>- Require highly skilled operator |
| 8 | Fluorescence Method | Use of light sources of a specific wavelength for molecule excitation in the targeted substance to a higher energy level. | - High spatial coverage<br>- Quick and easy scanning for leaks | - Medium to be detected must be naturally fluorescent. |
| 9 | Capacitive Sensing | Sensors use the variations in dielectric constants between seawater and hydrocarbons to detect existence of hydrocarbons. | - Can be employed for detection in non-metallic targets. | - Requires direct contact with medium<br>- Case of false alarms reported<br>- Buoyancy effects may carry leaking medium away from the sensor vicinity. |

 

*Table 1: Continuous External Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 10 | Electromechanical Impedance-Based Methods | Use of variations in structural mechanical impedance instigated by the incidence of pipeline damage for detecting leakages | - Capability to utilize a single piezoelectric transducer to serve both as a sensor and an actuator. | - Only applicable for metal pipelines<br>- Operational limitations in high temperature environments |
| 11 | Accelerometers | Use of vibro-acoustic measuring device for monitoring low-frequency pipe-shell vibrations, to detect leakages on exterior of pipe valves | - Used only in short pipeline segments or in sensitive locations<br>- Quick detection of leakage | - Requires stable constant power supply<br>- Sensor has internally fixed range & time constant<br>- Cannot measure rotation around its axis |

*Table 2: Continuous Internal Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 1 | Pressure Point Analysis | Leakage determined through the comparison of the measured values against the running statistical trend of the previous measurements. | - Low cost of implementation<br>- Low level of instrumentation<br>- For small leakages that cannot be detected by other methods | - Affected by batch processes<br>- May easily lead to a false alarm<br>- No indication of leak location or size beyond proximity of sensing position. |
| 2 | Mass or volume balance methods | Involves the use of Mass Conservation principle. If a leak occurs, the system has been opened and mass escapes and this results in a decrease in the measured mass flow at the outlet and an increase in the mass flow at the inlet. | - Low cost<br>- Portability<br>- Straight forward<br>- Insensitive to noise interference<br>- Most widely used technology<br>- Does not require long hours of tuning | - May take a long time<br>- Dependent upon the accuracy of the pipeline instrumentation<br>- Not applicable to gas line since line pack changes are large<br>- Not applicable for leak localisation |
| 3 | Statistical Systems | Use of Hypothesis test ($H_0$ = No leak) and ($H_1$ = Leak), used to check whether there is enough data for the statistical variable to be a plausible part of the leak hypothesis and if it is, sends out an alarm. | - It is appropriate for complex pipe system<br>- It could be used for leak localization<br>- It is very easy<br>- It minimizes rate of false alarm<br>- It is also suitable for real time application | - There could be noise interferes<br>- Some leaks could be hidden in the noise thus preventing them from being detected. |

 

*Table 2: Continuous Internal Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 4 | Real Time Transient Model (RTTM)-based Systems | Use of mass, momentum, energy and equation of state to determine flow rates and the difference between predicted and measured values of flow variable for leak | - For monitoring line packing and unpacking<br>- It can minimize false alarms<br>- It can detect leaks of less than 1% of flow<br>- It could estimate leak size accurately | - It is very expensive<br>- It requires extensive instrumentation<br>- Complex models require trained user<br>- Models may require SCADA support |
| 5 | Negative Pressure Wave | Leaks result in pressure drop, a negative pressure wave is generated and received by 2 pressure sensors installed to identify leaks via time difference of arrival | - Fast response time<br>- Suitable for leak localisation | - Its incapability of locating leak<br>- Not been exploited in long pipeline<br>- Effective for large instantaneous leaks |
| 6 | Extended-RTTM (E-RTTM) based Systems | Leak detection system calculates expected flow rates at the inlet and outlet, and these expected values are then compared to the measured flow values $F_0$ at the inlet and $F_L$ at the outlet. | - High rate of accuracy<br>- It can minimize false alarms<br>- It can detect leaks of less than 1% of flow | - Expensive to use<br>- It requires extensive instrumentation<br>- Models may require SCADA support |
| 7 | Leak Detection using SCADA | Uses pipeline pressures and flow rates to calculate flow balances. When it detects a difference in one section and next section, alert is issued at a remote control centre | - Provides quick interface or several sensors<br>- Possible to obtain real data simulation<br>- Constantly monitor systems and automatically process and record data | - Expensive to install and operate<br>- It requires extensive instrumentation |

*Table 3: Non-Continuous Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 1 | Inspection by Helicopter | Use of helicopters which fly along pipeline routes, by inspection by Laser, Leak Sniffers or Infra-Red | - High accuracy and reliability<br>- Requires no stoppage of operations | - High cost of rentals<br>- Operations may be affected by bad weather condition |
| 2 | Smart Pigging | Use of special pipeline pigs to obtain valuable information about existing leaks in pipelines. Pig is introduced and guided out of the pipeline | - High accuracy | - Expensive to run<br>- May require stoppage of operations |

 

*Table 3: Non-Continuous Leak Detection & Monitoring Systems*

| S/N | LDS Method | Principle | Advantages | Disadvantages |
|---|---|---|---|---|
| 3 | Tracking Dogs | Use of specially trained dogs to recognize the odour of certain compounds injected into pipeline, and dogs led sniffing along the right-of-way path. | - Good for short pipeline segments<br>- Used to narrow down the leak site<br>- Trained dogs are more sensitive | - Not effective for prolonged operation for more than 30–120 minutes due to fatigue |
| 4 | Trained or Experience Personnel | Trained personnel walk along pipelines and search for leakage in pipeline through visual observation, smelling odour, noise or vibrations generated. | - Very simple method<br>- Done with minimal operational tools<br>- Not expensive in equipment cost. | - Require leak to persist for long<br>- Expensive due to manpower<br>- Limited to time of year |
| 5 | Soil Monitoring | Inoculation of pipeline with small amount of tracer chemical which seeps out of the pipe in the event of a leakage and is detected by an instrument | - Very low false alarms<br>- High sensitivity<br>- Good for detecting very small leaks. | - Very expensive<br>- Not for exposed pipeline leaks<br>- Time consuming |
| 6 | Remotely Operated Vehicles (ROVs) | Designed to interact with extremely hazardous subsea environment while the master human operator is located in a safe place to remotely control the slave robot's motions | - Durable for performing subsea pipeline inspection tasks that cannot be accessible by dog, pigging or human divers. | - High cost of operations |
| 7 | Autonomous Underwater Vehicles (AUVs) | Use of AUVs in subsea pipeline inspections which have reduced the extent of human operator involvement in unmanned vehicles through the implementation of intelligent control machinery | - Good for remote and hazardous site<br>- Lower cost of maintenance<br>- Higher operation safety<br>- Easy to detect leak visually | - Extremely high cost<br>- Bad weather may affect work<br>- Effectiveness may be limited depending on technology used |
| 8 | Gas Sampling Method | Use of a flame ionization detector housed in a hand held or vehicle mounted probe to detect methane or ethane. | - Sensitive to small gas concentrations<br>- Immune to false alarms<br>- Portable | - Very slow, time consuming<br>- Expensive<br>- High cost of monitoring |
| 9 | Flow Monitoring Devices | Measurement of rate of change of pressure or mass flow at different sections of the pipeline. Leakage is inferred when pressure differs significantly. | - Ability to monitor continuously<br>- Non-interference with operations<br>- Low cost and Continuous monitoring | - Inability to pinpoint location<br>- High rate of false alarms<br>- Prone to false alarms |

**4. Discussion**

A good leak detection system must comply with API guidelines on leak detection which include sensitivity, accuracy, reliability and adaptability/robustness, which are geared towards accomplishing the ultimate goal of the industry at zero release of the product. There is also the need to ascertain which of the methods was the right and best method which calls for more detailed study of leak detection and leak localization. But for this, there may be no single technique to be used due to their individual various limitations and thus it may be required to combine two or more methods to obtain the better leak detection method. Such hybrid methods should be further developed for future beneficial use. These methods can be combined with online monitoring for quick and accurate detection. This requirement for leak detection system to provide quick and efficient recognition of pipeline leakage and proper attention promotes the possibility of considering the use and the need to design a real-time intelligent leak detection and localisation system.

To determine the exact leak location is very essential and thus requires further investigation, with some literatures noting that many methods cannot detect the exact point of the leak. The big issue of false alarms by some leak detection systems warrants more efforts especially to devise a means of denoising the system to avoid false alarm. There is also a need to work on a method which will not only detect but that could localize multiple leaks in a pipeline or multiple leaks in different pipelines or devices within the same facility. There is the need for thorough review of available historical data for those methods using artificial intelligence and machine learning, regarding facilities performance parameters and for the collection of sufficient data in order to develop more robust detection algorithm. For the leak detection systems that employ the use of sensors, there is concern for persistent failures of sensors but sensor nodes are smart enough to autonomously re-organise themselves to share sensing and data transmission tasks when some nodes fail. Thus, the scalability of the pipeline leakage detection sensor network is another research challenge when the coverage of the pipeline network is huge.

Again, it is a fact that leaks can only be accurately detected if the incident is within the vicinity of the monitoring sensor and thus the accuracy of leak detection systems becomes questionable if the leaks are not within the receptive fields of the sensors. Sensors deployed for remote monitoring of pipelines are employed to perform both sensing and communication functions, however, the challenge of how to cover a monitoring region efficiently and relay the obtained measurements to their neighbouring nodes is also challenging, which impact on the network performance. The other concern by researchers on leak detection systems is that further efforts are required to reduce cost and improve effectiveness of these systems and more efforts would need to be made to test the integration and workability in terms of cost and effectiveness. There is also the need to operate the process efficiently, in order to actuate, measure and record leaks.

## 5. Conclusion

After the aforegoing detailed and extensive review, it could be concluded as follows:

1. That Leak Detection Systems do not and cannot eliminate leaks but it can potentially reduce its impact through earlier detection and remedial action.
2. That one or more methods can be combined to give a simple Leak Detection Systems (LDS), as no single leak detection method is applicable to all pipeline situations and no one method is universally applicable. Thus we may be required to combine two or more methods to obtain the better leak detection method, such hybrid methods should be further developed for future beneficial use.
3. That in line with the above in (2), it is suggested the mathematical model methods can be used to draw and narrow down the leak locations while the physical methods can then to close out the exact leak location. Thus, these methods can be combined with online monitoring for quick and accurate detection.
4. That despite the avalanche of advanced leak detection technology, the human role in pipeline monitoring is still very important because remote monitoring does not always detect every small leak or slow leaks, but responsible neighbours need to be aware of the signs of a pipeline release.
5. Proper pipeline maintenance, effective pipeline monitoring for timely detection of leakage and even leak prediction remain the best solution, as early leak detection permits rapid responses to stop leakage while prompt identification of pipeline leaks also improves safety and protects the natural environment.
6. Any Leak Detection System for a pipeline should be designed based on the pipeline for which it is developed and its choice should be based on a fit-for-purpose approach and on the operating parameters (pipeline size, length, instrumentation design).

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