Leak Detection Methods—A Technical Review

R. Ramadevi, J. Jaiganesh and N. R. Krishnamoorthy

Abstract For safe transmission of various fluids or gases leakage detection in pipelines is very important. The leak of hazardous/dangerous fluids and gases can cause loss of property and lives (e.g., the Bhopal gas tragedy). Hence review of various available technologies should be necessary in order to identify a technology which provides an easy, adaptable, flexible, inexpensive, and efficient approach for real-time distributed data acquisition and monitoring. Based on review one can able to know that which technology has a very low false alarm rate and cost effective one etc. In this paper the performance and ability of the different systems is compared in terms of their leak detection capability.

Keywords Leak detection · Review methods · Pipeline · False alarm

1 Introduction

Pipelines are commonly used to deliver petroleum products, natural gas, liquid hydrocarbons, and water to consumers and industry for various applications. The movement of chemical products from place to place (e.g., natural gas, crude oil, and many other chemicals) is commonly carried out through a pipeline network. While transporting these products hundreds of miles, the pipes pass through various regions which include highly populated areas. It is essential to take measures and exercise care in those regions when chemicals are being transported. There have been many leakage accidents around the world, causing great losses of lives and properties.

R. Ramadevi (✉) · J. Jaiganesh · N. R. Krishnamoorthy
Sathyabama Institute of Science and Technology, Jeppiaar Nagar, Rajiv Gandhi Road, Chennai 600119, India
e-mail: ramadevi.eni@sathyabama.ac.in

J. Jaiganesh
e-mail: jaiganesh.eni@sathyabama.ac.in

N. R. Krishnamoorthy
e-mail: krishnamoorthy.eni@sathyabama.ac.in

A. Kumar and S. Mozar (eds.), *ICCCE 2018*,
Lecture Notes in Electrical Engineering 500,
https://doi.org/10.1007/978-981-13-0212-1_14

These types of accidents may occur in chemical industries, manufacturing industries, ships, or in any regions where pipelines are used. The reasons could be welding defects, corrosion, or erosion of external and internal walls in pipelines.

Pipeline degradation may also occurs because of stresses caused by changes in pressure and the deformation of the pipeline caused by soil dislocations, leading to the formation of micro-gaps and wear. When toxic chemicals are transported, the properties of those chemicals as well as suitable environmental conditions must be kept in mind in order to avoid any chemical reactions. So, it is necessary to study the advantages and disadvantages of existing leak detection methodologies.

In this work, seven important parameters are considered when comparing the performance of various methods. They are leak sensitivity, location estimate capability, operational change, availability, false alarm rate, maintenance requirement, and cost and power consumption. Out of these, the major parameter in almost all the methodologies faces problem is the false alarm rate.

A false alarm is highly undesirable for the following reasons.

- They generate additional work for the monitoring user.
- They reduce the confidence level of the user.
- A real leakage may be overlooked due to false alarms.

Close to 1,000 gas leakage incidents have occurred. Since LPG contains a propane and butane mixture which is highly inflammable and must be prevented to avoid any explosion. Concerned with environment protection and the costs of cleaning up oil spillages, more and more oil and gas production and transport companies are using pipeline leak detection systems on their main pipelines.

2 Leakage Detection Methodologies

Leakage detection methodologies are broadly categorized into three systems.

(a) **Hardware-based system**

These are systems that use hardware, special sensing devices for gas leak detection. As there are various types of sensors and instruments available it can be further subclassified as: acoustic [1], optical-based sensors, soil inspection [2], ultrasonic flow meters, and vapor sampling [3, 4].

(b) **Biological-based system**

This type of system does not use any sensing devices, instead it uses experienced personal to inspect the pipeline beds using either visual inspection or handheld instruments for measuring gas flow, or dogs trained to smell the leak [1]. In this system the pipeline is inspected for leak at regular interval of time among odor or sound and on hyper spectral imaging with advanced satellite (by [5–7]).

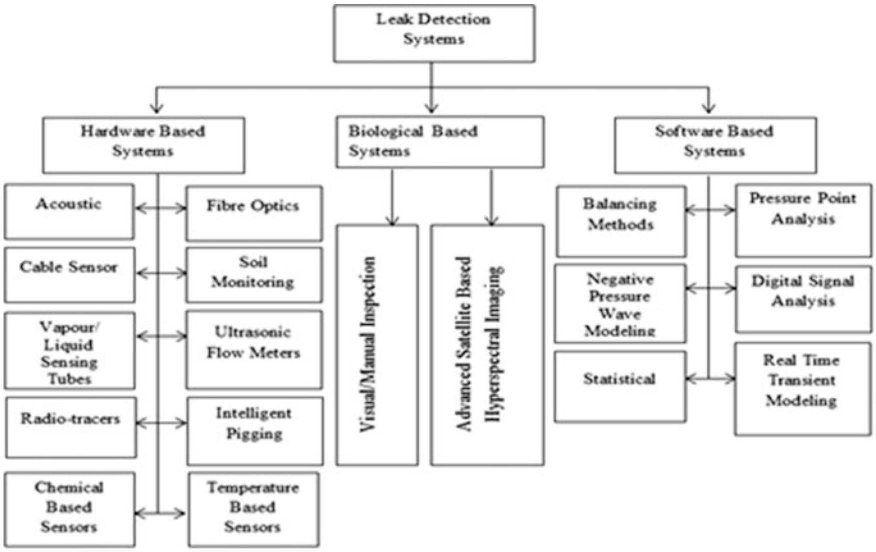

Fig. 1 Categorization of leak detection methods

(c) **Software-based system**

This type of method use different kinds of computer software package. The software implements different kinds of algorithms to monitor the condition of process parameters, such as pressure, temperature, flow rate, or other pipeline parameters. The software system depends on various techniques, namely pressure-based system-acoustic/negative pressure wave, pressure point analysis, real-time transient modeling by using a dynamic model-based system, statistical analysis and digital signal processing, flow/pressure change detection and mass/volume balance [8, 9]. Figure 1 presents major methods of leak detection techniques.

2.1 Hardware-Based System

2.1.1 Acoustic Method

The gas which is getting released at the leak point produces an acoustic signal as it flows through the pipe. This signal is used for leak detection and to record noise present inside the pipeline. Continuous monitoring can be attained by placing acoustic sensors outside the pipeline as shown in Fig. 2, which are placed at the desired distance (in meters) apart [10]. The gap between two acoustic sensors plays

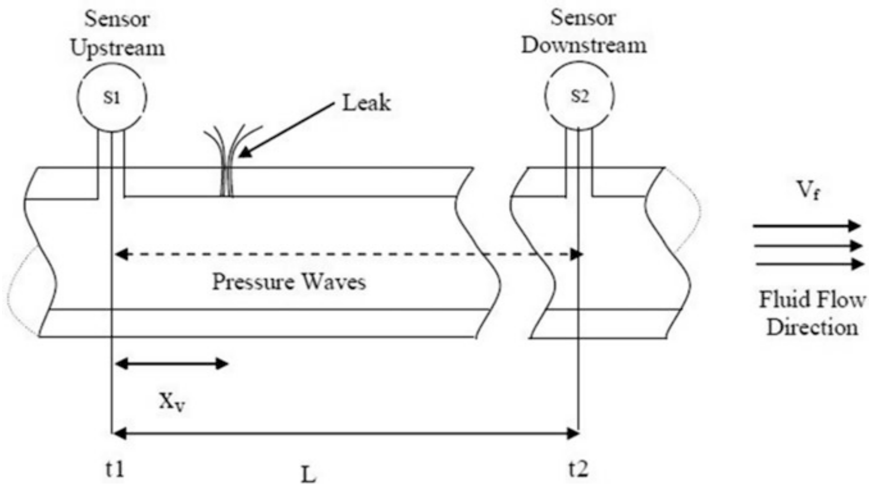

Fig. 2 Acoustic methods

a major role in determining sensitivity of the method. If the sensors are separated by a large distance, it will ultimately increase the risk of an undetected leakage, whereas placing them too close to each other will increase the cost [11].

When leakage occurs a noise signal is generated since fluid is moving out of the leak. The wave of this noise signal propagates the properties of fluid flowing through the pipeline and then the acoustic detector detects the corresponding wave and the leak [1, 12]. The problem with leak detection in longer pipelines is that it requires a large number of sensors and consequently increases the cost and is difficult to maintain, making it impractical also. Unwanted noise signals from the surroundings can be added to the original signal leading to difficulty in minute leakage detection.

2.1.2 Optical Methods

Optical methods are subdivided into two parts, namely active and passive [6, 13]. The active method uses a radiation source for scanning the area, whereas in passive methods there is no need for a radiation source because it depends on the radiation generated by the gas only. The active method illuminates the area above the pipeline bed by using a radiation source. The techniques for active monitoring technology include tunable diode laser absorption spectroscopy [14], laser-induced fluorescence [15], and coherent anti-raman spectroscopy (CARS) [16].

Active methods

The amounts of radiation which are absorbed or reflected by natural gas molecules is analyzed and if significant change or variation in absorbed and scattered light is

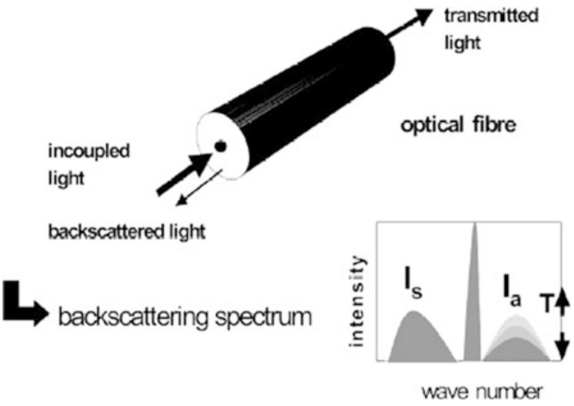

Fig. 3 Optical fiber use in backscatter imaging

detected above a pipeline bed, then a leak exists. There are different active methods for the optical detection of leaks, such as the LIDAR (light detection and ranging) method, diode laser absorption, millimeter wave radar systems, and backscatter.

Millimeter wave radar systems

In this method, the radar signature of the gas pipeline is generated. A gas like methane is lighter than air and the difference in density can produce a specific radar signature so as to detect a leak, but the major disadvantage is that it is highly expensive [17].

Backscatter imaging

This technique is also expensive, and for illuminating the scene a carbon dioxide laser is used. An infrared camera is used to capture the scattering signature, and the image revealed by the camera shows the location of leak on the pipe as shown in Fig. 3 [18, 19].

Passive methods

In the presence of hydrocarbons, the optical properties of fiber optics are affected thus providing another way of detecting gas leaks. Fiber optic sensing provides details of gas concentration and leak locations. Generally, lasers and optical detectors are used to record transmission characteristics.

Thermal imaging

To detect leaks, Weil [20] uses the difference in temperature of the leaked gas and the surrounding environment. This method is appropriate from ground and aerial vehicles, and is also successfully implemented on autonomous robots. Figure 4 shows the thermal image of a leaking pipeline. Thermal images are expensive. The major drawback is if the escaping gas has a similar temperature to that of the surrounding environment, then the leak cannot be detected.

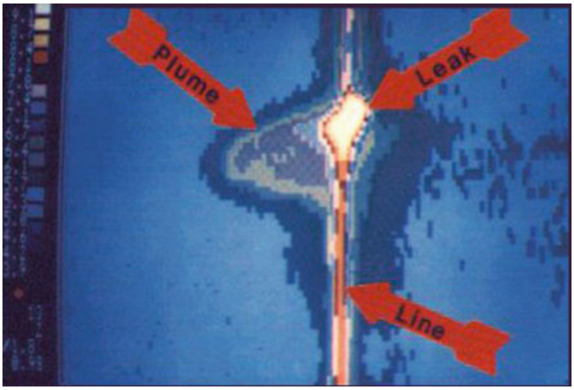

Fig. 4 Detection of a leak by thermal imaging. https://www.propublica.org/article/pipelines

Multi-spectral or multi-wavelength imaging technique

This method can be used in absorption or emission mode. Emission mode can lead to detection of leakages if the temperature of the gas escaping is much higher than the surrounding air. In absorption mode, absorption of background radiation is recorded at multiple wavelengths to generate a map of the gas concentration. The advantage is that leak detection takes place even if there is no significant difference between the escaping gas and the surrounding environment. It has a much lower possibility of generating a false alarm giving it added value. A major disadvantage of this method is that imaging sensors are highly expensive.

Gas filter correlation radiometry (GFCR)

Tolton [21], make use of a sample of the target gas as a spectral filter, where incoming radiation splits into two different directions when it passes through the narrow band pass filter. One of the cells is filled with the gas of interest (called the correlation cell) and the other one is empty. A spectral filter comprised of the correlation cell is used to remove the energy from the incoming beam at wavelengths corresponding to the absorption lines of the gas. Radiant fluxes from the two paths are measured using IR detectors and on the basis of the result it is decided if a gas leak is present. This method can detect leaks from an altitude of 300 m.

2.1.3 Soil Monitoring

Soil monitoring involves injecting the gas in the pipeline with an amount of tracer compound [22]. The tracer can be chemical or a non-hazardous or highly volatile gas, which will leave the pipe in exactly the same place as the leak (if a leak occurs). To monitor the surface above the pipeline, instrumentation is used to detect a leak by moving devices along it [23] or through probes installed in the soil close to the pipeline. Samples are collected and analyzed using a gas chromatograph [24]. Advantages of this method are a reduced false alarm rate and high sensitivity.

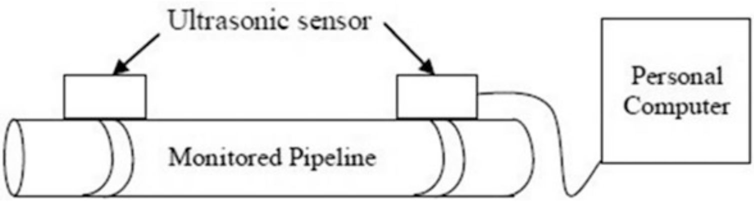

Fig. 5 Ultrasonic flow meter method. https://en.wikipedia.org/wiki/Leak_detection.4.1

A disadvantage is the high cost factor because a trace of the chemicals should be added continuously to the pipe during the detection process.

2.1.4 Ultrasonic Flow Meters

These systems were designed by Controlotron [25, 26] and later taken up by Siemens Industry Automation division [27]. In this system it is considered that the pipeline consists of a series of segments. Every segment is surrounded by two site stations which consist of a clamp-on flow meter, a temperature transducer, and a processing unit as shown in Fig. 5. All site stations measure or compute various parameters like volumetric flow rates, gas and ambient air temperature, sonic propagation velocity, and site diagnostic conditions. A master station collects the entire information obtained on or from various site stations. The computation process of the volume balance is done by the master station comparing the values obtained through site stations. The variation in the gas volume at the inlet and outlet of each pipeline segment provides necessary leak information. A small span of integration periods are used to show large leaks very quickly, while a long span of integration periods is needed to detect smaller leaks [28, 29].

This method provides accurate results but the major disadvantage is retrofitting to buried pipelines would be difficult.

2.2 Biological-Based System

In this process of detection, trained dogs are used because of their high sensitivity towards smell. The sensitivity based on various target/defect compounds, is in the range of 10 parts-per-billion (ppb) to 500 parts-per-trillion (ppt), in laboratory conditions [30]. A soap bubble screening method is also used for precisely locating smaller leaks [31, 6]. In this method, the operator sprays soap solution on different components of the pipeline, parts of the pipeline, or suspicious surfaces of the pipe. Usually it is preferable to apply this solution at the valves and piping joints because these areas are the places most prone to gas leaks. This method is rapid and the cost is low. Therefore it is helpful for routine inspection procedures. This method has the advantage that it requires no special equipment and results in the immediate localization of the leak upon detection, an advantage over the other techniques. The main disadvantage is the frequency of inspections determines the detection time, which is usually very small. The accuracy of detecting a leak greatly depends on the observation, experience, and scrupulousness of the employed personnel.

2.3 Software-Based System

A method based on software depends on information gained about flow, pressure, and temperature at certain regions of the pipeline. The performance efficiency and ability of a software-based leak detection system is determined by analyzing a series of factors of the existing methodologies. The necessary things to be kept in mind to evaluate the performance of leak detection systems are [32]: ability of the estimation of leak position, the speed of detection and the accuracy in determining leak size. The summarization of the very important parameters provided by each detection technique includes these criteria. Various abbreviations are used in the table below: yes (Y), no (N) for detection, slow (S), medium (M), fast (F) for detecting speed, and low (L) and high (H) for cost of the technique. A dash shows the inapplicability of the particular feature.

Table 1 provides a comparison of various leak detection techniques on the basis of power, size, location, response, and false alarms.

Table 2 shows information about assorted parameters, namely cost, monitoring speed, and easy usage, etc.

2.3.1 Mass/Volume Balance

The basic principle of this method is mass conservation between input and output. A change in the input and output gas mass or volume can be used for the determination of the leak [33, 7]. The amount of gas leaving a section/portion of pipeline is being removed from the amount of gas entering this section/portion and if the difference in the volume is above a certain predetermined limit, a leak alarm will be generated by the medium. The mass/volume can easily be computed using the readings collected by monitoring of some of the frequently used process parameters: flow, pressure, and temperature, along with various other parameters.

Leak in the pipe and its detection depend on calculating the change of inlet flow and outlet flow measurements in the pipeline. The meter accuracy and its tolerance is responsible for the sensitivity of the mass/balance method. The efficiency of this method mostly relies on the leak size, rapidity of measuring the balance, along with calculation by the system and the accuracy of the measuring instruments/devices being used. The installation of the system is easier when compared to other existing methods because it depends on instrumentation which is readily available. The operator can easily understand, learn and use it in an improved way, hence reducing

Table 1 Comparison of various leak detection techniques

Method	False alarm	Leak size	Location	Smallest leak	Response time
Acoustic emission	1 false alarm/ year	Nominal flow medium	±30 m	10% of pipeline diameter, 1-3%	15 s to 1 min
Fiber optic sensing	No	Large, medium and small leaks	1 m	50 ml/min	30 s to 5 min
vapor sensing	No	Large, medium and small leaks	0.5% of monitored area	100 l/hr	2–24 h
Ultrasonic flow meters	No	Nominal flow small	100 m range for 100 km pipeline	0.15%	Near real time
Volume balance	Many	Indicated by difference in flow	–	Greater than 5% of flow	Bigger leak-faster response
Reflected wave	Many	Related to size of propagated wave	Difficult to locate if near measuring section	10%	Fast
Pressure analysis	Many	Very small	Depends on position of transducers	50 ml/min	Delayed response
GLR	Very Less	Indicated by mass flow variation	Almost entire length	10%	Fast

errors. A further advantage of this system is its comparatively low cost. The usage of balancing techniques is restricted to leakage detection during varying flow or shut in and slack line conditions. It takes a longer time to detect small leakages. For example, a 1% leak needs approximately 40–60 min to detect [34]. This method is not favorable when it comes to locating the leak and another drawback is that unless thresholds are adapted, it generates frequent false alarms during transient states.

2.3.2 Pressure Change

In this process, pressure sensors have an important role and are mostly installed at the extremes of pipelines. Initially, a predefined limit is set when the steady state occurs and if the pressure falls below this limit (as shown in Fig. 6) then a leak exists. The usage of low pass filter is an advanced and improved technique for use with long pipelines, and is done with respect to the occurrence of pressure disturbances.

Table 2 Comparisons based on other parameters

	Visual inspection	Soap screening	Aconstic	LIDAR	Diode laser absorption	Millimeter radar	Backscatter imaging	Broadband absorption	Fiber optic cable	Thermal imaging
Cost	L	L	H	H	M	H	H	L	H	H
Detection speed	S	S	F	M	M	M	M	M	F	M
East retrofiting	–	–	Y	–	–	–	–	–	N	–
Easy usage	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Leak localization	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Leak size estimation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Multi-Spectral imaging	Gas filter correlation radiometry	Soil monitoring	Vapor sampling	Ulrasonic flow meters	Mass/ Volume balance	Negative pressure valve	Pressure point analysis	Statistical	Digital signal processing
Cost	H	M	H	H	H	L	L	L	H	H
Detection speed	M	M	S	F	F	F	F	F	F	F
East retrofiting	–	–	N	N	N	Y	Y	Y	Y	N
Easy usage	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Leak localization	Y	Y	Y	Y	Y	N	Y	N	Y	Y
Leak size estimation	Y	Y	N	Y	N	Y	Y	N	Y	N

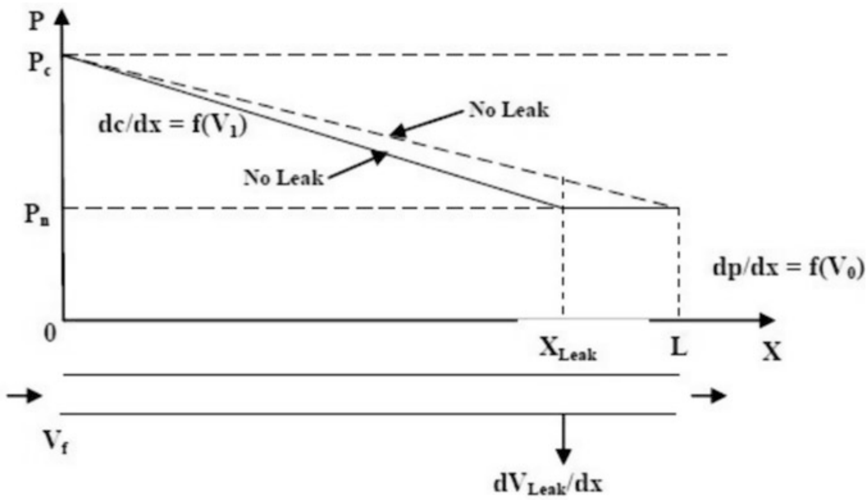

Fig. 6 Showing the variation in pressure

2.3.3 Change in Flow

In this method the operator uses a predefined figure like a reference figure, which is used as a model for possibilities in the change of flow. The leak detection here is assumed to take place when in a specific time period the rate of change of the flow observed is higher than a predefined figure.

2.3.4 Negative Pressure Wave

It is known that the spot where pressure drops or where there is a sudden variation in pressure leads to increase in the leakage probability, which generates the wave of pressure upstream and downstream. This generated wave is known as a negative pressure wave and the readings are collected by using pressure sensors which are placed at extremes of the pipe [35].

For determination of the leakage, the leakage algorithm collects the reading (information) from the pressure transducer placed on the pipeline. Different methods, including a support vector machine [36], are used for the same purpose. The time difference between the moments at which the two pressure transducers ends, senses the negative pressure wave and is used to identify the leak location. If the leak is near to one end of the pipe, then the corresponding transducer will be the first to receive the pulse and the amount of time required to receive the pulse at the other end is used to detect the leak location with a good degree of precision. Negative pressure wave-based leak detection systems, such as ATMOS Wave [37, 38], can estimate the size of the leak.

Another approach of detecting leaks by means of pressure waves is by manually or intentionally generating the transient pressure waves. This is done by closing and opening valves at intervals of time [39, 40]. The presence of a leak will partially reflect these pressure waves and allow for the detection and location of the leak. A disadvantage of using pressure waves is that it become impractical to detect leaks in long-distance pipeline.

2.3.5 Pressure Point Analysis

Pressure point analysis is a fast leak detection software technique based on the principle that in the presence of a leak, the pressure drops or changes will occur inside the pipeline [41]. This technique is made efficient by continuous measurements of the pressure at various locations on the pipeline. The presence of a leak can be detected by statistical analysis of the measured values and by comparing the measured mean value of pressure with the threshold set point value. If the measurement is below the threshold value, then leakage is detected, otherwise there is no leakage. The patent [41] of this leakage detection technique is with EFA Technologies Inc. which offers PPA™ as part of their LEAKNET™ leak detection system along with MassPack™, PPA™ which has been proven to work in different environment condition (high and low temperature, pressure) [42] and leak rates below 0.1% of flow but it is not a dependable technique during transient flow.

2.3.6 Statistical Analysis

An easier method of detecting gas leakages, without the need to design a mathematical model is by using a statistical analysis technique. The corresponding analysis is done on various measuring parameters like flow and pressure at different locations along the entire pipeline bed. The system will generate a leak alarm only if it detects a pattern consisting of a relative change in flow and pressure parameters [43].

The thresholds for leakage are set after a tuning period of the system during which the parameter is placed under different operating conditions in the absence of a leak. To reduce the false alarm rate, the tuning process is done for a long period of time [44]. During the tuning period, the initial data will be affected in the presence of a leak and the system behavior will be considered as normal due to which the leak would not be detected unless and until it grows large enough in size to go beyond the threshold limits given during the tuning process.

A leakage of 0.5% was detected [44] but even smaller leaks can be detected. Instruments being used should have a high resolution and be accurate and precise. Statistical analysis can also be used for determining the leak location and position. The main advantage of this technique is its flexibility of use, being adaptive and robust to different pipeline configurations. The main disadvantages of using this method are the difficulty in estimating leak volume and considerably high costs.

2.3.7 Digital Signal Processing (DSP)

In this method, leaks can be detected by measuring flow rate, pressure, and temperature parameters obtained by using digital signal processing [45]. The response of a known flow change is measured during the setup phase. Measurement of parameters is used together with DSP to identify changes in the system response. DSP allows the leak response to be recognized from noisy data. In the beginning, this technique was provided only for liquid pipelines [46] but later it was even considered for gas pipelines. There is no requirement for a mathematical model for the pipeline; its main motive is to extract leak information from noisy data. Similar to a statistical approach, if during the set-up phase a leak is already present in system, it would never be detected until its size grows. Disadvantages are its high expense, implementation difficulty.

3 Conclusions

A review of the various leak detection techniques has been presented in this paper. Comparison of different leak detection techniques based on various features such as cost, false alarm rate, approximate leak location capability etc., has been provided. Of all the techniques, the optical fiber method is the most effective in all aspects except for cost and maintenance factors. Acoustic methods provided reasonable detection sensitivity but under low surrounding noise it became incapable. Hence, an ultrasonic flow meter is used for surrounding noise. Biological methods like the surveying of pipelines depend greatly on the experience and meticulousness of the employed personnel. So, it cannot be used frequently, and as a result software methods were introduced. Software methods helped to continuously monitor real-time leak detection, providing better accuracy on the position of leaks and the size of leaks.

References

1. Hough JE (1988) Leak testing of pipelines uses pressure and acoustic velocity. Oil Gas J (United States) 86:47: n. pag. Print
2. Tracer Research Corporation (2003) Patent product described in the website of Tracer Research Corporation. www.tracerresearch.com
3. Bose JR, Olson MK (1993) TAPS's leak detection seeks greater precision. Oil Gas J, April Issue, pp 43–47
4. Turner NC (1991) Hardware and software techniques for pipeline integrity and leak detection monitoring. In: Proceedings of offshore Europe, vol 91. Aberdeen, Scotland
5. Carlson BN (1993) Selection and use of pipeline leak detection methods for liability management into Journal of Applied Engineering (JOAE), 2(2), February-2014 (Volume-II, Issue-II) 32 the 21st century. In: Pipeline infrastructure II, Proceedings of the international conference of the American Society of Chemical Engineers, ASCE

6. Murvay P-S, Silea I (2012) A survey on gas leak detection and localization techniques. J Loss Prev Process Ind
7. Scott SL, Barrufet MA (2003) Worldwide assessment leak detection capabilities for single and multiphase pipelines, project report prepared for The Minerals Management Service. Offshore Technology Research Centre, Texas
8. Griebenow G, Mears M (1988) Leak detection implementation: modelling and tuning methods. Am Soc Mech Eng Pet Div 19:9–18
9. Liou JCP, Tian J (1994) Leak detection: a transient flow simulation approach. Am Soc Mech Eng Pet Div 60:51–58
10. Brodetsky I, Savic M (1993) Leak monitoring system for gas pipelines. In: IEEE international conference on acoustics, speech, and signal processing, ICASSP-93, vol 3. IEEE, pp 17–20
11. Loth J, Morris G, Palmer G (2003) Technology assessment of on-line acoustic monitoring for leaks/infringements in underground natural gas transmission lines. Technical Report, West Virginia University, USA
12. Klein WR (1993) Acoustic leak detection. Am Soc Mech Eng Pet Div (Publication) PD, vol 55, pp 57–61
13. Reichardt TA, Einfeld W, Kulp TJ (1999) Review of remote detection for natural gas transmission pipeline leaks. Report prepared for NETL, Sandia National Laboratories, Albuquerque, NM
14. Hanson RK, Varghese PL, Schoenung SN, Falcone FK (1980) Absorption spectroscopy of combustion gases using a tunable IR diode laser. In: Laser probes for combustion chemistry, ACS symposium series, vol 134, pp 413–426
15. Crosley DR, Smith GP (1983) Laser induced fluorescence spectroscopy for combustion diagnostics. Opt Eng 22:545–553
16. Eckbreth AC, Boncyzk PA, Verdieck JF (1979) Combustion diagnostics by laser, Raman and fluorescence techniques. Prog Energy Combust Sci 5:253–322
17. Gopalsami N, Raptis AC (2001) Millimeter-wave radar sensing of airborne chemicals. IEEE Trans Microw Theory Tech 49:646–653
18. Kulp TJ, Kennedy R, Delong M, Garvis D (1993) The development and testing of a backscatter absorption gas imaging system capable of imaging at a range of 300 m. Appl Laser Radar Technol; In: Proceedings of society of photo-optical instumentation engineering, vol 1936, pp 204–212
19. Kasai N, Tsuchiya C, Fukuda T, Sekine K, Sano T, Takehana T (2011) Propane gas leak detection by infrared absorption using carbon infrared emitter and infrared camera. NDT E Int 44(1):57–60
20. Weil G (1993) Non contract, remote sensing of buried water pipeline leaks using infrared thermography. ASCE, New York, NY, USA, pp 404–407
21. Tolton T, Boyd A (2004) Concept for a gas-filter correlation radiometer to remotely sense the atmospheric carbon dioxide column from space. J Atmos Ocean Technol 21:837. https://doi.org/10.1175/1520-0426(2004)021%3c0837%3AACFAGC%3e2.0.CO%3B2
22. Lowry W, Dunn S, Walsh R, Merewether D, Rao D (2000) Method and system to locate leaks in subsurface containment structures using tracer gases, US Patent 6,035,701
23. Praxair Technology Inc (2007) Seeper trace leak detection for in-situ gas storage, sequestration and EOR sites
24. Thompson G, Golding R (1993) Pipeline leak detection using volatile tracers. Leak Detect Underg Storage Tanks 1161:131–138
25. Controlotron Corporation (2005) Controlotron non-intrusive ultrasonic flowmeters. Brochure
26. Controlotron Corporation (2006) Controlotron system 1010 family of non-intrusive ultrasonic flowmeters. Brochure
27. Siemens Industry Inc Clamp-on leak detection solution for enhanced pipeline management. Brochure, Aug 2011
28. Bloom D (2004) Non-intrusive system detects leaks using mass measurement. Pipeline Gas J 231(7):20–21

29. Siemens Industry Inc SITRANS F: Ultrasonic flowmeters FUS-LDS leak detection system operating instructions, Sept 2011
30. Johnston J (1999) Canine detection capabilities: operational implications of recent R & D findings. Institute for Biological Detection Systems, Auburn University
31. Liu AE (2008) Overview: pipeline accounting and leak detection by mass balance, theory and hardware implementation
32. Stafford M, Williams N (1996) Pipeline leak detection study. Technical Report, Bechtel Limited
33. Parry B, Mactaggart R, Toerper C (1992) Compensated volume balance leak detection on a batched LPG pipeline. In: Proceedings of the international conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers, pp 501–501
34. Doorhy J (2011) Real-time pipeline leak detection and location using volume balancing. Pipeline Gas J 238(2):65–66
35. Silva R, Buiatti C, Cruz S, Pereira J (1996) Pressure wave behaviour and leak detection in pipelines. Comput Chem Eng 20:S491–S496
36. Chen H, Ye H, Chen L, Su H (2004) Application of support vector machine learning to leak detection and location in pipelines. In: Proceedings of the 21st IEEE instrumentation and measurement technology conference, 2004. IMTC 04, vol 3. IEEE, pp 2273–2277
37. de Joode AS, Hoffman A (2011) Pipeline leak detection and theft detection using rarefaction waves. In: 6th pipeline technology conference
38. Twomey M (2011) A complimentary combination. World Pipelines, pp 85–88
39. Elaoud S, Hadj-Taleb L, Hadj-Taleb E (2010) Leak detection of hydrogen-natural gas mixtures in pipes using the characteristics method of specified time intervals. J Loss Prev Process Ind 23(5):637–645
40. Mpesha W, Gassman S, Chaudhry M (2001) Leak detection in pipes by frequency response method. J Hydraul Eng 127:134–147
41. Farmer E, et al (1989) A new approach to pipe line leak detection. Pipe Line Ind (USA) 70(6): 23–27
42. Scott S, Barrufet M (2003) Worldwide assessment of industry leak detection capabilities for single & multiphase pipelines. Technical Report, Department of Petroleum Engineering, Texas A&M University
43. Zhang X (1993) Statistical leak detection in gas and liquid pipelines. Pipes Pipelines Int 38(4): 26–29
44. Zhang J, Di Mauro E (1998) Implementing a reliable leak detection system on a crude oil pipeline. In: Advances in pipeline technology, Dubai, UAE
45. USDT (2007) Leak detection technology study for pipes act. Technical Report, U.S. Department of Transportation
46. Golby J, Woodward T (1999) Find that leak [digital signal processing approach]. IEE Rev 45(5):219–221
47. Mandal PC (2014) Gas leak detection in pipelines & repairing system of titas gas. J Appl Eng (JOAE), 2(2), pp 23–34
48. Sivathanu Y, Narayanan V (2003) Natural gas leak detection in pipelines, Technology Status Report