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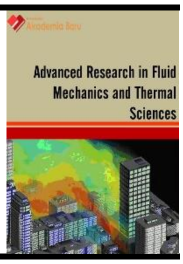

A Review on Water Leakage Detection Method in the Water Distribution Network

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ABSTRACT

Leak detection in transmission pipelines is crucially essential for safe operation. Pipeline leak detection systems play a crucial role to minimize the probability of occurrence of leaks and hence their impacts. The distribution pipelines in case of urban water supply need to monitor for contaminants such as microbial growth, internal corrosion of the pipe's material and other deposits. In addition to the loss of water resources, the contaminant can be infiltrated into the piping system. These contaminants affect not only the quality of the water but also the smoothness of the water pipe flow due to the pressure loss and additional frictions. Therefore, it is essential that this problem be quickly detected and repaired. Today there are many available technologies in the domain of leak detection. This paper will provide you with a fundamental understanding of the operating principles of currently available pipeline leak detection technologies.

1. Introduction

The accidental arrival of liquid from pipelines described as a leak. Pipeline leak may result, for instance, from poor quality or any ruinous reason, because of sudden changes of weight, destructive activity, splits, deserts in channels or absence of support. By and large, the detrimental impacts related to the event of the leak may exhibit significant issues and, in this way, releases must immediately be detected, located and repaired. The effect of a leak even turns out to be progressively genuine when it is worried about the fundamental supply of crisp water to the network. In addition to the waste of resources, contaminants may infiltrate into the water supply. The possibility of environmental health disasters because of deferral in the discovery of water pipeline leaks have instigated research into the advancement of techniques for pipeline leak and contamination detection.

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Public water pipeline systems stretch out for thousands of kilometres, comprising of many pipe sections associated by joints. These pipelines exposed to traffic and other surface burdens which overemphasize the pipes and joints. Leakage of water happens from mains and administration associations at joints and fittings, from break because of over the top forced loads and openings caused by corrosion. In early years, since the estimation of unaccounted-for item was believed to be immaterial and the expense of the vitality was very low, leakage in water dispersion frameworks was to a great extent overlooked. This perspective of leakage the executives has been continuously changing since the mid-1980s, for both economic and environmental reasons. Therefore, in the past decades, investigate in water assets has been fundamentally coordinated toward groundwater and transport-related topics. Then again, the water lack alongside the fundamentally more significant expense of vitality for water conveyance and treatment, have started a quickly developing enthusiasm for spillage control issues. On the national ground, real urban communities across the Kingdom of Saudi Arabia (Riyadh, Jeddah and Medina) rely upon desalination for over 90% of their water needs [1]. The water desalinated in vast plants and after that distributed to urban communities and towns. This dissemination required the development of an extensive system of pipelines. The issue of water leakage from these pipelines causes clean water loss, energy loss and a noteworthy increment in water contamination with dangerous synthetic compounds and metals. It accounted for that 30% of the water transported over the Kingdom of Saudi Arabia (KSA) is lost through leakage [2]. This considered as a high amount given that the present desalination limit is assessed at six million cubic meters per day and is required to ascend to the excess of 10 million cubic meters for each day throughout the following five years [3]. An average expense of 0.75 USD per cubic meter, it is evaluated that the desalination cost misfortunes add up to 820 million USD every year. This sum does exclude transportation distribution and other losses. Moreover, the issue of leakage infers conceivable infiltration of hazardous contaminants into the water distribution system.

1.1 Water Supply Systems

Water supply systems have become a lot of vital since water demand has enhanced speedily within the developing countries. It is because of the urbanization, industrialization, improvement of living standards and economic conditions. In contrast, accessible sources of water keep decreasing in variety and capability [4]. Throughout the last twenty years, there are increasing necessities to enhance the operation of installation systems, whereas rising the surroundings so that their behaviour is understood. Therefore, the total method is optimized [5].

The World Health Organization tips for drink quality states that water free from cloudiness, colour, odour, objectionable style and at an affordable temperature alleged to potable water [6-8]. The distribution pipelines just in case of urban installation must be monitored for contaminants like microbe growth, internal corrosion of the pipe material and alternative deposits. These contaminants not only influence the standard of the water, it also effects the smoothness of the water flow due to the pressure loss and extra frictions. This drawback can also cause chronic renal problems if it is used directly for drinking or even cooking [9,10]. Figure 1 shows a typical urban water distribution setup. From the figure, it seems that the freshwater treated before it distributed to the community. The treated freshwater to be rigorously channelled to the users as a significant drawback will occur. The main disadvantage is that the underground pipes leakage and it's the most causes to the wastage of the scarce water resource.

Meanwhile Figure 2 shows the typical water treatment plant setup. Generally, there are five steps in the water treatment process namely the screening, chemical mixing, flocculation, filtration and chlorination. These stages are to ensure that the water is disinfected in which typically done by adding chlorine-based disinfectant to water. It will kill water-borne microbes, bacteria and viruses.

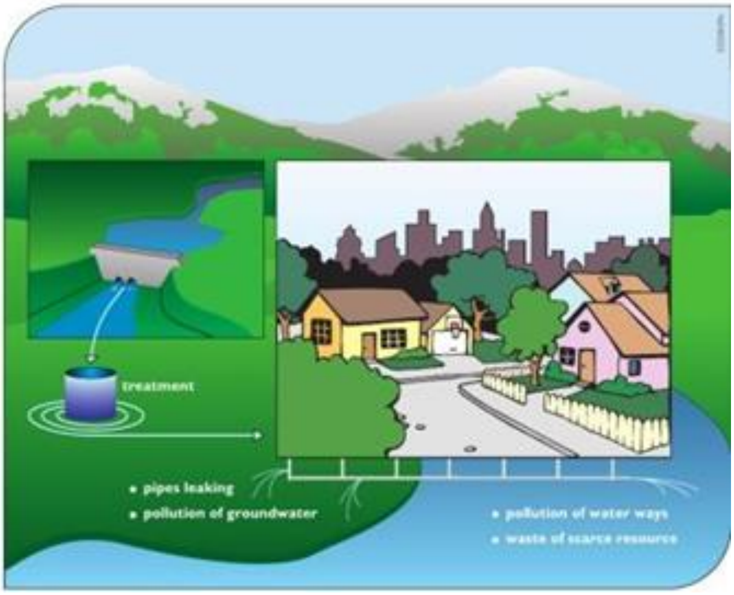

Fig. 1. Typical urban water distribution setup [11]

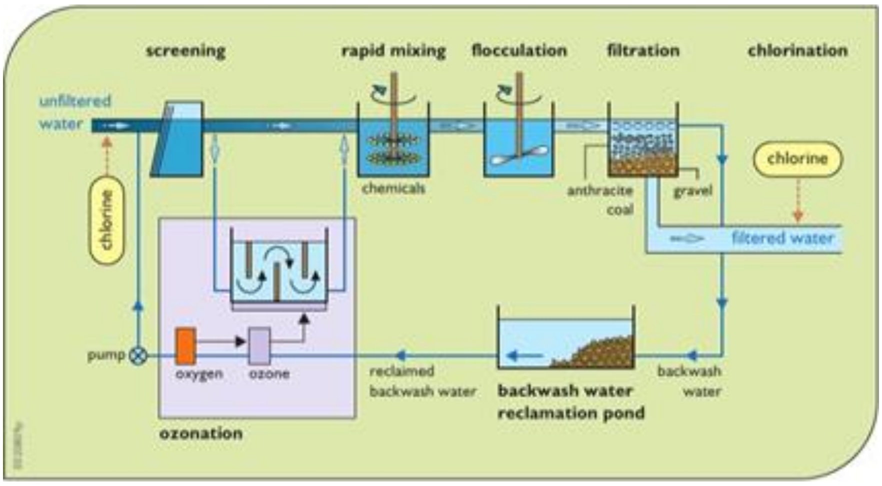

Fig. 2. Typical water treatment plant setup [11]

2. Leak Detection

Various experimental techniques using field tests for leak detection have been reported early by Brones and Schaffhaussen [12] and Hunaidi and Chu [13]. The most popular field tests are flow direction indicators, tracer gases, subsurface radar, earth sensitivity changes, infrared spectroscopy, microphones, and odorant and radioactive tracers. In those early stages, researchers mostly used simple and direct methods to detect pipeline leaks. These methods were mainly based on limit values checking of some important system variables. Methods based on acoustic effects were applied as shown in Figure 3. Acoustic measurements have been utilized in detection and pinpointing of leak locations in both gas and liquid pipelines for many years. The first acoustic device for pinpointing leaks in buried pipelines was patented in 1935 by Wilsky [14].

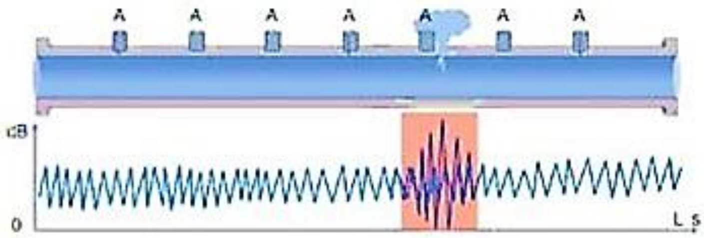

Fig. 3. acoustic leak detection

De Read [15] discussed detection methods that use ultrasonic and magnetic flux pigs. However, these simple methods can only detect leak at a rather late stage. In addition, they are expensive and time consuming. Moreover, such tests, in general, are sensitive to many environmental and operational variations, and therefore, are prone to signaling false alarms. In recent years, methods have been developed to detect leaks more accurately, and in an early stage. Such methods are based on system models, parameter identification and state observers. An early survey of methods on the state variable approach is reported by Wilsky [14] and on parameter identification by Siebert [16]. Methods based on both the parameters and state variable approaches were developed by many investigations such as those by Isermann [17], Isermann [18], Billmann and Isermann [19] and Isermann and Freyermuth [20]. Wang *et al.,* [21] have recently developed a method to detect and locate leaks in fluid transport pipelines by using only pressure measurements. Their method, which does not require flow measurements, on the contrary to other methods, is based on statistical autoregressive model. However, this statistical approach fails to detect small leaks and has been verified by using a short experimental water pipeline only.

Liou [22] proposed a leak detection method based on transient flow simulations whose feasibility was demonstrated by numerical simulations and physical laboratory tests. Figure 4 show a real time transient model. A similar method was tested by Loparo *et al.,* [23] using field trials on real pipeline data where data noise in pressure and flow measurements are considered. The presence of noise, however, was found to limit the ability of the algorithms to detect leaks as well as inducing frequent false alarms.

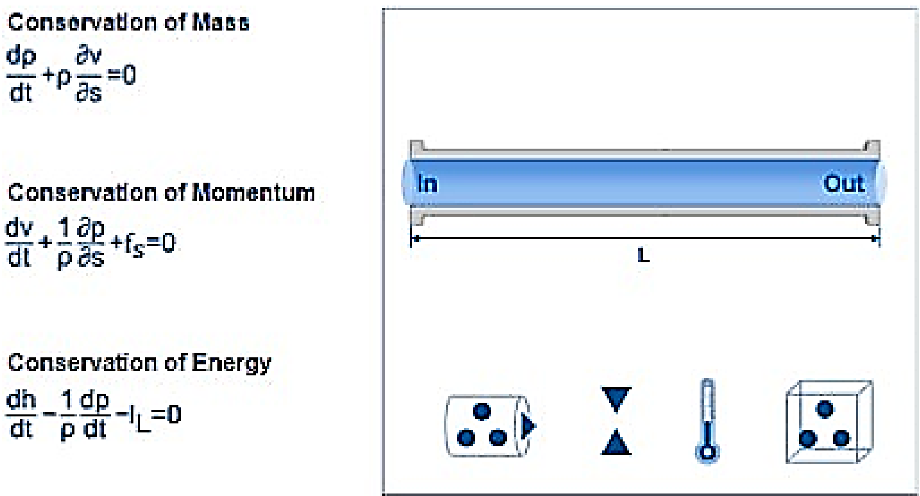

Fig. 4. Real time transient model

It was concluded that further work is needed to develop means to avoid noise amplification in such algorithms. Isermann [24] addressed the problem of early detection of faults in dynamic systems by calculating some internal quantities based on measured input and output signals and their causal dependence. Parameter and state estimation methods and parity models are used to determine these internal quantities. An inference mechanism determines possible faults based on fault-symptom causalities and approximate reasoning methods; e.g. probabilistic or fuzzy logic methods. The application of this approach to leak detection in pipelines was not addressed. In general, leak detection methods used in pipeline automatic supervision can be divided into two major classes. Methods belonging to the first class are mainly based on directly measurable quantities such as inflows, outflows, pressures and temperatures. The second class relies, alternatively, on non-measurable quantities such as internal state variables, model parameters and characteristic quantities of the pipeline system. Methods of this later class obviously are based on modelling and estimation methods. It should be noted that most of the previous research in leak detection [12-15,23,25-27] is concerned with methods that can be related to the abovementioned first class. Much less attention, however, was directed to develop methods of the second class, which depend on non-measurable quantities. Recently, Khulief and Shabaik[27] developed a multiple-model state-estimation scheme, which utilizes the non-measurable state variables, to detect and locate single leaks in an oil pipeline system. Laboratory tests demonstrated the applicability of scheme and revealed that the scheme's accuracy is dependent on the transducer's accuracy.

One of the important methods for detecting water distribution system leaks involves using sonic leak-detection equipment, which identifies the sound of water escaping a pipe. These devices can include pinpoint listening devices that make contact with valves and hydrants, and geophones that listen directly on the ground. In addition, correlating devices can listen at two points simultaneously to pinpoint the exact location of a leak. Leak in pressurized water pipes generates noise. The magnitude and frequency of the noise depends on many factors such as the shape and size of the leak, pipe material and the water pressure inside the pipe. In general, there are three predominant acoustic leak detection systems [28]. These include acoustic listening devices, leak noise correlators and tethered hydrophone systems. Although each system has its own merits, it also has limitations, as well. Leak noise correlators can be used to detect the acoustic signal generated by the leak, which travels simultaneously through both the pipe wall and the water column in the pipeline [29]. Accelerometers are surface mounted sensors that measure the vibration induced into the pipe wall by the leak noise. By measuring the vibration at two or more locations, the source of vibration can be identified.

Leak noise correlators can also use hydrophones in lieu of accelerometers. Unlike accelerometers, hydrophones are underwater microphones that are placed in contact with the water column and detect the acoustic noise transmitted through the water column. Hence, the hydrophones must be inserted into the water via openings on fire hydrants or other outlets along the pipeline [30]. A third acoustic leak detection technique is a tethered hydrophone system. This utilizes a hydrophone sensor tethered to a cable that is connected to a data acquisition system so that the hydrophone can be listened to while it is in a pipeline [31]. Recently, a free-swimming leak detection acoustic is being addressed [28]. The concept of the free-swimming stems from the realization of the advantage of placing a sensor very near to the leak (no further than a pipe diameter); which is anticipated to provide a highly sensitive leak detection method. One of the major challenges in designing such a sensor was to provide for the sensitive detection of the acoustic signal generated by a leak, with minimal interference from noise generated by the movement of the device as it traverses the pipeline.

Mergelas and Henrich [32] indicated that methods of leak noise correlators, although suitable for small pipes, are not reliable for the case of large diameter pipes. Mergelas and Henrich [32] developed methods that depend on passing acoustic sensor along inside the pipe and detect the point above the leak noise signal was greatest. Gao *et al.,* [33] investigated the behavior of the cross-correlation coefficient for leak signals measured using pressure, velocity, and acceleration sensors. They indicated that pressure responses using hydrophones is effective for measurements where small signal-to-noise ratio, but a sharper peak correlation coefficient can be estimated if accelerometers are used. The authors validated their theoretical work test data from actual water pipes. Gao *et al.,* [34] considered the delay between two measured acoustic signals to determine the position of leak in buried water distribution pipes. The authors compared different time delay estimators for the purpose of leak detection in buried plastic water pipes. The results were validated by experimental results. Results of spectral analysis between two sensors were presented. Also, normalized cross- correlation using various correlation methods for measured signals was also presented.

2.1 Major Leak Detection Methods

The major leak detection methods available in the market are listed below in Table 1. The principle of working of each method is given and the advantages as well as the limitation of each method are outlined.

3. CFD Studies in Leak Detection

Computational Fluid Dynamics (CFD) is a powerful engineering tool that can be used at the different stages of the water distribution networks development and operation. For example, during design stage, the CFD can be used to design the optimum setup or configuration of the system. As the CFD is a non-intrusive tool, therefore several important parameters can be tested on the system before the system is being constructed. The CFD tool has matured to the level where the results are reliable and can be used as basis for the real system.

As indicated by Mansour *et al.,* [36], various trial approach has been produced to detect the leakage. Among the conventional field tests are flow direction indicators, tracer gases, subsurface radar, earth sensitivity changes, infrared spectroscopy, microphones, and odorant and radioactive tracers. Meanwhile the most recent leakage discovery techniques are developed which dependent on the system models, parameter identification and state observers, and the state of the art of CFD. Two of the earliest investigators via latest approach are Billman and Isermann [37-39]. They demonstrated that early identification by utilizing numerical methodology can be utilized as a feature of the leakage detection method.

Table 1
Major Leak Detection Methods [35]

Method	Advantages	Limitations
Acoustic Principle: Locating the loudest sound of leak by audible sound transducer placed on the ground surface above the pipe	• Most commonly used • Acceptable accuracy • Simple to carry and move	• Depends on the operator skills • Not effective for small leaks • Affected by background noise • Depends on pipe size, material, water table level, system pressure, frequency range • Loose soil muffles sound • Exact pipe location must be known • Suitable more for hard surfaces • Depth less than 2 m
Acoustic with correlation Principle: A correlation program uses two vibration transducers signals installed on the pipe at two locations bounding the leak with pipeline information	• Good accuracy • Relatively acceptable price • Minimal operator training	• The leak should be located between the two listening points • Accuracy relies on accurate input of pipe dimensions and materials • Not suitable for plastic pipes • Good sensor contact is essential • Accuracy depends on the closeness of the leak to measuring points • Sometimes there is no access to the pipe close to the leak
Infrared thermography Principle: Locating the temperature differences in soil caused by leaking water using infrared radiation	• Its non-contact, nondestructive • detection • The ability to inspect large • areas from above ground with 100% coverag • Locate subsurface leaks as well as the additional capability to locate voids and erosion surrounding • pipelines	• High cost • Requires significant operator experience • Detection depends on the soil characteristics, leak size, and pipe burial depth • Application is limited by ambient conditions
Ground penetrating radar Principle: Uses electromagnetic radiation of the radio spectrum and detects the reflected signals from subsurface structures. It detects voids created by the leaking water or anomalies in the depth of the pipe due to soil saturation with leaking water	• Can be used in a variety of media • It can detect objects, changes in material, and voids and cracks • Penetration depth could be up to 15 m in dry soil	• The depth of penetration depends greatly on soil type • An experienced operator is needed for correct interpretation of radiograms • Considerable expertise is necessary to effectively design, conduct, and interpret GPR surveys • The cost of GPR equipment and software is relatively high • Relatively high energy consumption can necessitate large cumbersome batteries for extensive surveys more than 10 h
Chemical (gas tracer and fluoride testing) Principal: A tracer in the pipe escapes through the leak and detected at ground surface	• It may be an effective method in case of emergency that requires isolating the pipe with no flow	• Very expensive • Time consuming • Exact pipe location must be known • Limited to depth less than 2 m
Mechanical Principal: A series of holes drilled in	• Low cost • Can be used to support acoustic methods	• Exact pipe location must be known • Depends on the leak size • Careful drilling is required

the soil above the pipe to allow water rise near the leak		• Requires significant physical effort
Inside pipe sensor Principal: The sensor moves or swims inside the pipe to detect leaks internally	• Capable of detecting very small leaks in pipelines, • Can be inserted and retrieved from a pipeline without disrupting its flow • Collect information about leaks over many miles of pipeline with a single deployment Independent of pipe materials	• Expensive • Communication with sensor is not easy • Powering the sensor is time limited • Needs insertion-retrieval openings • No control on sensor path in pipe branching • Self-generated noise can affect the signal • Still under development
Sahara system (tethered sensor) Principal: A sensor Head attached to umbilical cable moves within a live pipeline with a tracking tool above ground surface	• Retrieval is easy • No power and communication problems • Possible upstream motion • It can detect leaks as small as 0.25 • gallons/h • Inserted into a pipeline while it remains in service • It can pinpoint the location of leaks within 2–3 feet • Accurate for all types of pipes • Working depth of 10 m	• Wire length is the limitation • Used for water mains only and not suitable for small diameters • Not easy to deploy • Cannot be directed in pipe branching

Mansour *et al.,* [36] completed CFD simulation by utilizing CFD commercial software. The k-ε turbulence model was utilized to determine a small leak in WDN pipeline as appeared in Figure 5. Both steady and unsteady simulations were done consider velocity of fluid at 2.5m/s and pressure in between 1 to 5 bars. Their outcomes have great concurrence with the hypothetical just as well as previous experimental data. They found that for small leaks, line pressure drop is not discernible, but pressure gradient is visible (see Figure 6).

Shehadah *et al.,* [40] additionally performed CFD simulation on leakage water pipe. They contemplated the leakage for steel pipe for various crack measurements and diverse liquid stream properties, for example, weights and speed. They approved their work with the experimental results. Their primary finding was the maximum velocity, total pressure, turbulence intensity is directly corresponding with the leakage mass flow rate with rupture area in pipelines.

In the meantime, Mora-Rodríguez *et al.,* [39] explored the interruption of contaminants into the leaked pipeline. To simulate this condition, they set negative pressure inside the pipeline. They guaranteed that they effectively showed the impact of interruption by utilizing theories of Torricelli and Favad (fixed and variable area discharged). López-Jiménez *et al.,* [41] likewise performed CFD simulation on water supply pipe. They examine the impact of various pressure level on the interruption of contaminants into the supply pipe. They additionally contrasted their outcomes and the theoretical approach.

Brunone *et al.,* [42-44] have done generous works with the simulation of the leakage of water pipe. His group utilized a transient way to simulate the impacts of the leakage or even to find the leakage site. They inferred that the transient approach is basic contrasted with the traditional technique for distinguishing the leakage, in any event for a simple piping system.

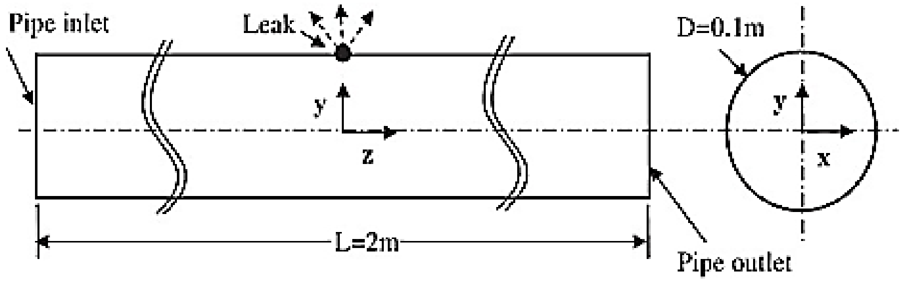

Fig. 5. Pipe model with leak Mansour *et al.,*[36]

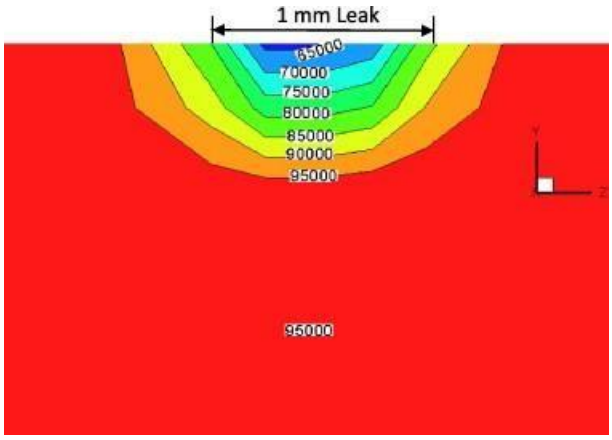

Fig. 6. Pressure (Pa) contours around leak [36]

4. Main Causes of Water Leakage

Compared to other water leakages in various cities of the world, the water leak at Riyadh city is considered the highest [45]. A detailed analysis of the study showed that extreme variation of leakage was also observed between the new and old parts of the city network. The three oldest areas of the city showed leakage levels between 59% and 80%; whereas, the leakage levels of newly developed areas were between 1% and 10%. The locations of the leak points were also studied. It was found that 80% of the total detected leaks were in the service connections. It was observed that most of leak points were located at house connections due to damages and cracks in the connection parts such as: couplings, elbows, valves, and saddle clamps. The possible causes of these damages or cracks were attributed to negligence of contractors during installation of pipe fittings house connections. It was observed that improper bedding and backfilling were the major two factors causing pipe connection damage. Improper bedding could impose excess bending on pipes, and consequently increased the amount of stresses on pipe fittings.

In addition, backfilling and bedding sand containing large and sharp stones resulted in scratching and puncturing the pipes and fittings. Furthermore, the cyclic nature of water supplies, pressure fluctuations, temperature change, and repeated surges could be contributing factors to the life of pipe fittings. In fact, many micrographs of fracture surfaces taken from different failed pipe fittings were indicative of fatigue failure.

5. Summary

Pipelines and thus also leak detection systems can be found in a wide variety of areas for various products. Accordingly, the challenges that the leak detection system faces vary depending on the application. At the end of the day, the question is which leak detection system is the right one? There is no one right leak detection system. The selection must always be made while taking into consideration the requirements placed on the application. That means it is necessary to decide for each application. Among other things, proper selection depends on the desired results, the cost of installation, operation, maintenance and servicing of the leak detection system and the installation conditions such as if a pipeline has to be dug up or uncovered. Modern leak detection systems function in a wide variety of environments and allow for individual adaptation to customer surroundings, guaranteeing optimal performance under all normal operating conditions.

6. Issues and Recommendations

The main issues in this study is the limitation in the major leak detection method available in the market. First limitation that should be highlight is the cost related to the leak detection method. Most of the method are expensive and considering the area to cover in water distribution network is huge, some of the method are not suitable to be used to detect leakage in the network. Other limitation in leak detection method is the size of the leakage. Some of the method are not effective to detect small leak that could be infiltration of hazardous contaminants into the water distribution system. The last limitation in the leak detection method is the method available in the market are unable to analyse the pressure profile in the pipeline.

Finally, the key stones of the presented review are summarized into a few recommendations.

i. Model-supported systems with the help of density profiles can portray an exact calculation of the contents of the pipeline. This can be used, for example, to financially evaluate the amount of product currently stored in the pipeline. This can be of great benefit, especially when it comes to long transport pipelines.
ii. In the case of theft, even the smallest leaks must be detected. This requires a particularly high sensitivity such as that offered by state-of-the-art leak detection systems.
iii. It is also possible for the leak detection system to analyse the hydraulic profiles. In this way, considering the elevation profile of the pipeline, it can illustrate the pressure profile and in the case of over or under pressure, e.g. undershooting the vapor pressure of the medium, set off an alarm indicating a ‘slack’ line condition.

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