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Investigation of leak detection systems for saltwater transmission lines

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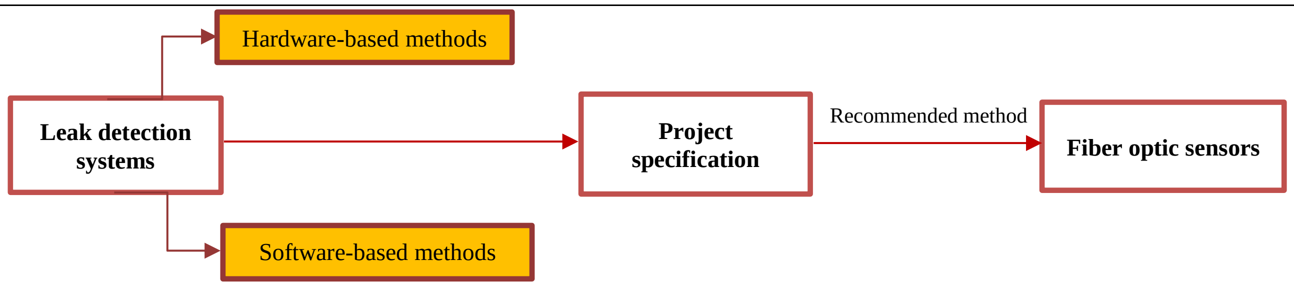
GRAPHICAL ABSTRACT



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ABSTRACT

The use of a proper leak detection system in pipelines is of crucial importance in water transmission systems. In these methods, we should consider the time and accuracy of leak detecting procedure for preventing energy loss and reducing environmental impacts. In these days, seawater transmission lines are used for cooling systems, and for injecting water into the oil wells to improve oil recovery. Due to the more environmental impacts of saltwater, the leak detection system must have appropriate accuracy and speed in leak detection. The purpose of this paper is to choose a leak detection system for a saltwater transmission line. First of all, the specifications of different leak detection systems are provided. Finally, according to the mentioned project conditions, the most suitable method -fiber optic system- is recommended for these conditions. The most important advantages of this system are high accuracy, rapid leak detecting, and the ability of online monitoring of other parameters, such as temperature distribution or detecting intrusion into the buried line areas. These abilities result in improving safety and optimizing operating costs.

1. Introduction

One of the methods to improve oil recovery is to inject seawater into oil wells by draining water from the sea and transferring it to the oil fields. The saltwater around the line can pose many environmental impacts, such as the destruction of farmland and living things, so it is essential to detect leaks quickly and accurately along the seawater transmission lines to oil fields. So far, different methods have been proposed and used for leak detection. These methods are usually defined in two parts:
-Methods based on external effects (hardware).
-Computational methods (software).

Li et al. (2021) have presented a leak detection method based on active thermometry and fiber Bragg grating (FBG) based quasi-distributed fiber optic temperature sensing. (Li et al. 2021). Adegboye et al. (2019) studied the different techniques of leak detection in pipelines and presented the strengths and weaknesses of each. Also, in this paper, a suitable technique for different conditions is recommended (Adegboye et al. 2019). Golmohamadi (2015) introduced various leak detection methods (software-based and hardware-based) and studied two methods for detecting leaks in transmission lines. First of all, hardware-based method which inspects the pipe by sending supersonic wave through the transmission lines. This method has tested in several pipes with different conditions and has provided excellent outcomes in short pipes. Secondly, software-based method that is rely on a hydraulic model of the pipe. According to the results of this study, the second method has high accuracy for long pipes (Golmohamadi. 2015). Boostani et al. (2015), compared leak detection methods based on optimization. A MATLAB code developed on an algorithm with a minimized objective function and the relationship between pressure loss and potential leakage locations. The results comparison of the observed data using the optimal method of leak detection techniques showed that in addition to choosing the appropriate way and calibration of the model, to estimate more accurately the location and amount of the leakage in the pipeline, field surveys and piezometer readings should be performed to determine the consumption pattern of the study area to identify the maximum number of unauthorized branches (Boostani and Khodashenas. 2015). Moavenian et al. (2011) two online leak detection methods were designed and simulated based on mass balance. The results showed that the technique could increase the sensitivity to leak detection from day to minute (Moavenian and Khorram. 2011). Hang-Eun Jeo et al. (2018) studied on optical fiber sensors. In this paper, the optical fiber sensors employed in

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environmental monitoring are summarized for an understanding of their sensing principles and fabrication processes. Numerous specific applications in petroleum engineering, civil engineering, and agricultural engineering are explored, followed by a discussion on the potentials of OFS (Optical Fiber Sensor) in manufacturing (Jeo et al. 2018). Research by Glisic and Inaudi (2003) reported several field application examples of fiber optic sensors, including leak detecting on saltwater and gas pipe networks, strain to monitor on gas pipe networks, and merged strain and temperature monitoring on composite transmission pipelines, and composite coiled tubing pipes (Glisic and Inaudi. 2003). Due to the environmental conditions of the project, and the presence of saltwater, that is dangerous for the surrounding area, this pipeline is considered as an environmental hazard. In this paper, some types of leak detection methods with their advantages and disadvantages have been presented. Finally, the best leak detection method considering environmental impacts has been chosen.

2. Materials and methods

Hardware-based and software-based methods are two common techniques for detecting leak. These methods are also known as externally and internally systems. Fig. 1 demonstrates the classification of different leak detection systems (Golmohamadi. 2015).

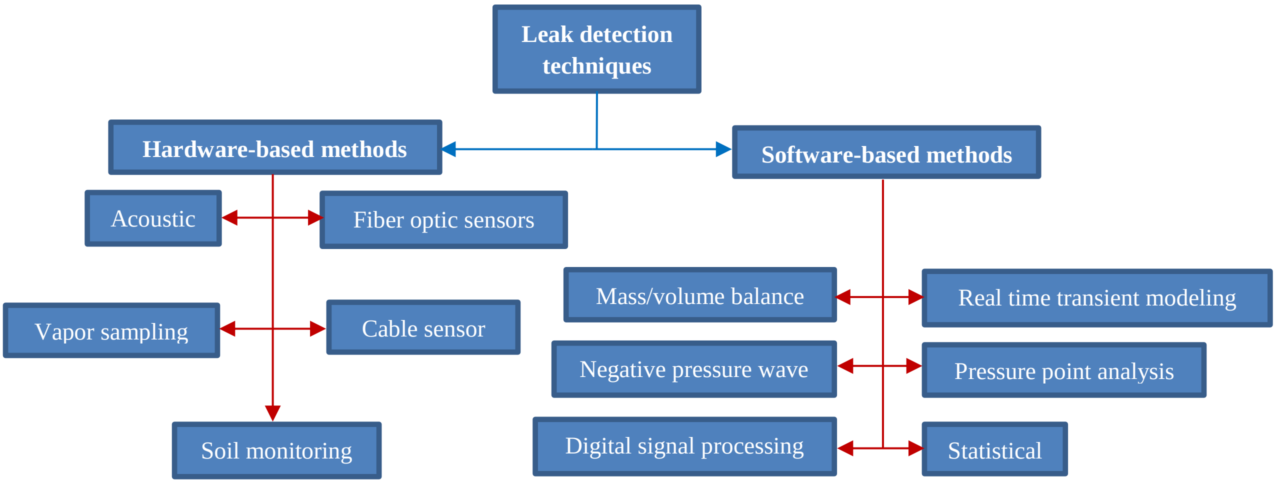

Fig.1. Different leak detection systems.

2.1. Hardware-based methods

Hardware-based methods are used to detect the location and presence of leaks by some instruments which are installed outside of the pipeline. These methods provide an excellent sensitivity in leak detecting and are so accurate in determining the leak location. However, the disadvantages of these methods are that they are too costly, and they are also too complex to be implemented. As a consequence, their application is limited to the places which are under high-risk condition, such as pipeline systems that are transferring a dangerous material near rivers (Murvay and Silea. 2012). Fiber optic systems, acoustic leak detection, vapor sensing cable, and liquid sensing cable-based systems are some examples of these types of methods.

2.1.1. Acoustic leak detecting

This method is based on producing an acoustic noise in the location of leak presence. Some acoustic sensors installed outside of the pipeline detect the internal signal and then make a baseline with particular characteristics. The self-resemblance of this signal is steadily tracked by sensors. The leakage presence causes a low-frequency acoustic signal detected by sensors. In case these signal's features are different from the baseline, the system will alarm (Fuchs. 1991). In the leak place, the tracked signal shows a higher amplitude, and it can contribute to detect the leak location. In these methods, cross-correlation is the most general approach in leak detecting. This approach usually depends on tracking the noise signal which happens when leakage occurs through the pipe. In the place where the leakage is expected, the leak can be detected by installing sensor on both sides of the pipeline (Fig. 2).

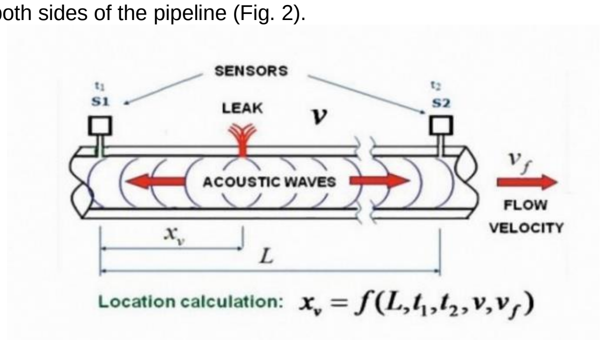

Fig. 2. Acoustic Sensors in Leak Detection (Golmohamadi. 2015).

The leak place can be recognized by speed of sound, duration time, and the spacing between sensor places. This would be determined by solving the following equation (Geiger and Werner. 2003):

$$d_1 = \frac{d - ct_{peak}}{2} \quad (1)$$

In this equation, d_1 is the spacing between the sensor (1) to the leakage point, d is the spacing between two sensors, c is the sound speed, and t_{peak} illustrates the time delay in the delivering of similar frequencies to every sensor. The efficiency of this method relies on the spacing between the sensor points, d. clearly, all variables of this equation can be determined from the experiment. The performance and precision of this system does not depend on the operator skills (Ghazali. 2012). Regarding to the benefits of using this method, the system can be monitored continuously. Although acoustic signals are appropriate in detecting the leakage location and the estimating of leak's size, in some cases, high background noise, such as noise which is created by pump equipment or vehicles, can affect the real leakage signal (Murvay and Silea. 2012). In addition, an important problem for the limited application of this method is its financial issues; installing numerous sensors that are essential in inspecting of the long pipelines according to this method is dramatically costly (Golmohamadi. 2015).

2.1.2. Fiber optic sensors

This technique includes the installation of a fiber optic cable along the whole length of the pipe. The material to be measured get in touch with the cable change the temperature of the cable. The distributed fiber optic temperature sensing technique offers the possibility to measure temperature along the pipeline. The principle of pipeline leak detecting in this technique depends on a simple concept: when a leak occurs at a particular place along the pipe, the distribution of temperature around the pipe changes. This change is localized both in space and in time and makes the algorithmic detecting of leakage relatively simple to implementation. The base of the temperature disturbance around the pipe relies on the kind of pipe and the area around it. Fig. 3 shows the position of the fiber optic sensor cable around the pipeline (Niklès et al. 2004).
The most usual impacts are as the following:

- The leaked liquid material higher temperature than the soil (Fig. 4-a).

- The leaked gas creates a local cooling owing to pressure release (Fig. 4-b).
- The leaked liquid affects the thermic features of the surrounding soil, especially thermic capacity, and changes the typical day/night temperature cycles.
- A warm plume is created in pipe surrounding
- In the multiphase pipelines, a combination of the mentioned impacts can happen.

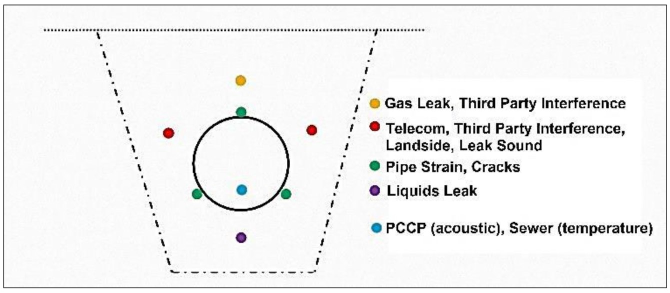

Fig.3. Specific positions of the fiber optic sensor cable around the pipeline.

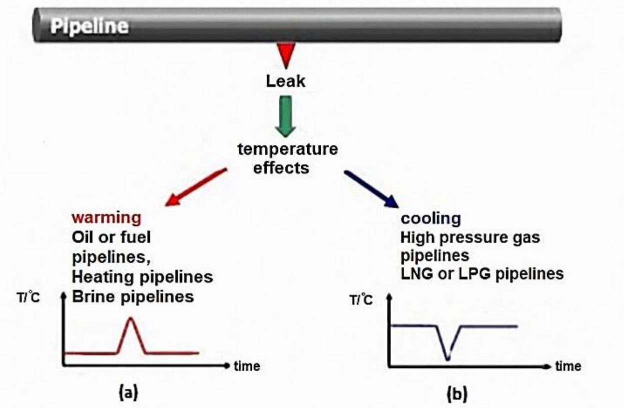

Fig. 4. Thermal behavior of warm (a) and cooling (b) fluid at the point of leakage.

The mentioned impacts affect the perfect cable localization around the pipe. In the underground liquid pipe, the most perfect place for the sensing cable is under the pipeline, however not in direct connection. (Mirzaei et al. 2013) (See Fig. 5).

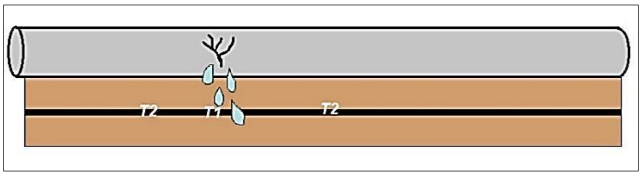

Fig. 5. Leak detection in buried liquid pipeline.

The changing in detecting time and the volume reflects the various local properties and in specific: Permeability and soil compaction, spacing between the leak and the sensor point and variation between temperature made by leak and the soil temperature. Although there are some disadvantages for fiber optic method, such as high costs, which limit the use of this method for pipeline monitoring, insensitivity to electromagnetic interference is one of the main advantages of fiber optic method (Ghazali. 2012).

2.1.3. Vapor or liquid sensing tubes

This method includes the implementing of a tube along the entire length of the pipeline. In case of leakage occurrence, the material transferred by the pipe affects the tube. In case of leak occurrence, some gas sensors at the end of the tube detects changes in gas concentration along the tube. The size of this change in gas concentration indicates the amount of the leakage. An electrolytic cell is attached to the inspected pipeline which diffuses a particular amount of test gas through the tube persistently. This gas goes through the entire length of the tube and when moves through the inspector section generates a final peak. The location of the leak is defined by obtaining the ratio of final peak delivery to leak peak delivery (Golmohamadi. 2015). Fig. 6 illustrates this method. As a drawback of this technique, the speed of leak detecting is deficient. Apart from that, it is not very practical for installing in long transmission lines due to the equipment price that is too expensive. The second disadvantage of this system is its problem in pipelines which are above ground or grave sites.

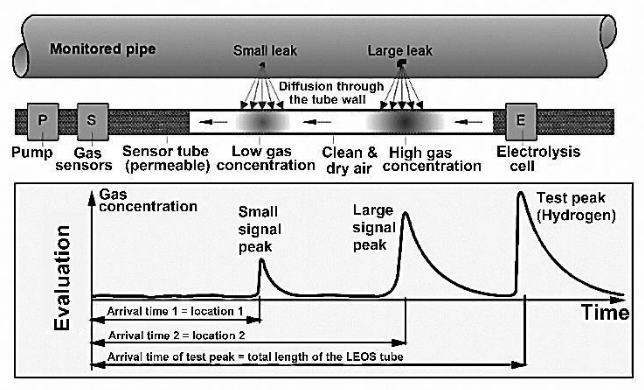

Fig. 6. Leak Detecting by Vapor Sensing Tube Method.

2.1.4. Liquid sensing cables

These cables are installed beside a pipe, and the most important task of them is an inspection of changes in energy pulses which have occurred because of impedance differentials. Energy pulses transmit consistently along the cable. A monitoring unit receive the reflections of energy pulses and create a map of them and then, save this map in a memory. The liquids on the sensor cable will affect its electrical features. This effect will lead to a difference in the reflection energy pulses at that place. This method is used to identify the place of a probable leakage. The time difference between input and reflected pulse would determine the exact location. (Golmohamadi. 2015). This method is applicable to detect multiple leak presence and also suitable in short pipelines.

2.1.5. Soil monitoring

This system uses a cheap and safe gaseous detector into the pipe. This detector is identified as a very volatile gas that escapes from the pipe where the leakage happens. The investigation of the soil above the pipe helps us to predict the existence of the leak and its place. This method provides some benefits, such as making low false alarms and also the ability to detect tiny leaks. However, the method is too expensive due to the fact that the detector should be injected through the pipeline permanently during the detecting process. In addition, this method is not practical in case of uncovered pipes (Golmohamadi. 2015).

2.2. Software-based systems

These methods rely on the assessment of pipeline hydraulic characteristics, such as flow and pressure. In general, the impact of these systems relies on the uncertainties related to the system's properties, operating properties, and gathered information.

2.2.1. Mass-volume balance

This is a technique based on the principle of conservation of mass. The principle states that the amount fluid enters the pipe section is equal to the amount of left fluid. The flow going into and exiting the pipeline networks can be measured easily. Any observed variation between upstream and downstream hydraulic parameters measurement which are larger than accepted threshold demonstrate the presence of the leakage (Murvay and Silea. 2012). This technique is susceptible to pipeline facilities' precision. One important drawback of this technique is the assuming of a steady condition. Therefore, the detecting time should grow for avoiding the possible false alarm. Hence, the response time to the leakage will be lasted more. As an example, a 1 % leak requires about one hour to be detected (Boostani and Khodashenas. 2015). Moreover, this method is not able to detect the location of the leak (Ghazali. 2012).

2.2.2. Real-time transient modeling (RTTM)

This method relies on solving the hydraulic flow models of the pipe using mass, momentum, and energy conservation equations. The discrepancy between the measured and calculated values of the flow determines the leak occurrence. The measurement of hydraulic parameters and temperature at both sides of the pipe are essential for creating this model. In addition, the design of a perfect system with a low range of false alarm needs a steadily monitoring system to inspect the noise level. This would lead to modification of the model. The main benefit of this technique is the ability of detecting tiny leaks, and it can predict the leak's size precisely. Apart from that, the delay in time of leakage detecting is insignificant. However, this technique is too expensive due to the fact that it requires the processing of massive data (Golmohamadi. 2015).

2.2.3. Negative pressure wave (NPW)

When a leak happens, the pressure in pipe drops abruptly at the place of the leak. This sudden change in pressure produces a negative pressure wave which goes through the pipe with a specified velocity in both direction of the pipe. The negative pressure wave is detected by two pressure sensors locating at the start point the and end point of the pipe. These sensors can recognize the leakage and localize it by measuring the time variation of the delivery times of the negative pressure wave at each sensor (Golmohamadi. 2015). The measured time in this technique is about two minutes, and the localizing of the leak has a 2% error. However, this method still is not applicable in long pipelines (Murvay and Silea. 2012).

2.2.4. Pressure point analysis pressure.

This technique identifies the presence of leakage by assessing the pressure data received from the pipe with a statistical trend that is taken in a particular duration along the pipe by monitoring equipment (Ghazali 2012). This technique depends on the principle of the pressure loss resulting of leak occurrence. A leak alarm will generate by the system when the newer data is significantly different from older records. Although this technique may acquire sensitive high accuracy, it is not certainly need exact instrumentation. Hence, the overall installation costs are not too expensive. In addition, this technique can detect the happening of leakage, but not the existence of it. Due to the fact that this technique considers change in pressure value as a leakage signature, it could create errors yielded because of the pressure drop which is not really related to the leakage.

2.2.5. Statistical

This system uses an enhanced statistical method to analyze the hydraulic parameters and temperature measurements of a pipe. This technique is suitable for complicated pipeline systems since it can be inspected steadily for variations in the line equipment. Moreover, this system has the ability to localize the leak point. This method also is used for various pipe systems (Murvay and Silea. 2012). The main purpose of this method is to detect leaks with minimum number of false alarms. In addition, it is proper for real-time applications mostly in pipeline systems in oil industries (Ghazali. 2012). The main drawback of this method is the noise interfering in the statistical analyses which prevents leaks from being detected (Golmohamadi. 2015).

2.2.6. Digital signal processing

In this technique, the reflection of the pipe to a particular input signal is determined in a specific time duration. Then, this reflection is compared to the following data. The difference in comparison of signal's properties. This method does not require a pipe model. The main issue of using this technique for leak detecting is that in this method, just leakage happening can be identified, not leak existence even the size of the existing leak rises significantly (Murvay and Silea. 2012).

2.3. Requirements to leak detection system (LDS)

API-1155 represent a framework to assess the various leak detection systems. API-1155 specifies four performance parameters:

- **Reliability**

Reliability (API-1155) is described as a way to assess the ability of the leak detection system to make precise alarms for presence of a leakage on the pipe, while operating within an envelope established by the leak detection system design. It follows that reliability is directly related to the possibility

- To identify leakage, given when leakage exists, and
- To wrongly predict leakage given when no leak has happened.

A technique is dependable if it continuously identifies real leaks without creating false warning.

- **Sensitivity**

Sensitivity (API-1155) is a combined measurement of the leak's size and the time needed for making a leak alarm. Minimum detectable leakage rate and leakage detecting time rely on each other. Lower minimum leakage detecting rates need longer leakage detecting times, and higher minimum leakage detecting rates allow lower leakage detecting times. The performance of a leak detection system is defined by using an OCP (Operational Characteristic Plot). There are some important things to note:

In long lasted leakage detecting times, for both leak detection system, the minimum leakage detecting rate converges asymptotically to a minimum limit value, the lowest possible leakage detecting rate. This parameter is mainly depending on the precision of the flow meters, and so it is almost not dependent on the leak detection system type. If the detecting time reduces, the minimum leakage detecting rate grow for both LDS (leak detection system). LDS #1 provides a better performance (lower minimum leakage detecting rates) than LDS #2.

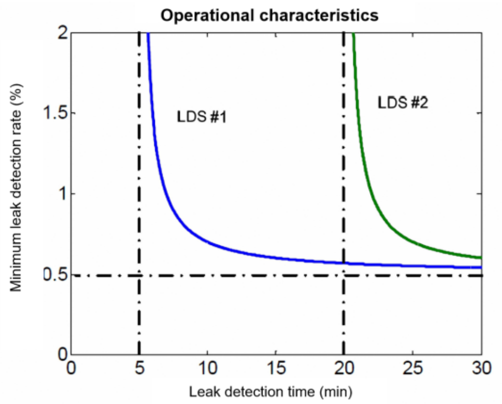

Fig. 7. Evaluating sensitivity using the operational.

- **Accuracy**

LDS may provide additional leak information such as leak location and leak rate. The validation of these leak parameter estimates constitutes another measure of performance referred to as accuracy.

- **Robustness**

Robustness (API-1155) is described as a measurement of the leak detection system's ability to continue to operate and provide helpful information, even under unstable conditions, or in a situation where data is lost or not accurate. Robust leak detection system usually can tolerate sensor fails using some kind of redundancy evaluation.

2.4. Project specifications

The aim of this project is to transfer water from onshore to the 4 delivery points. For this purpose, two steel buried pipelines are designed in parallel with a length of approximately 185 km. in this project, the transferring water is raw seawater. In addition, the route lines are near the farmlands, the speed and accuracy in detecting leaks are essential for the environmental considerations. The overview of the pipeline route in this project is shown in Fig. 8. In this project, various leak detection methods have studied, and according to the project conditions, the best method has been chosen.

3. Results and discussion

Various criteria can assess the performance of leak detection systems. According to the conditions of the project, the most effective approaches for choosing a leak detection system are the speed of detection and also the accuracy in locating the leak point.

- The accuracy of the acoustic leak detection method in detecting the leak location depends on the distance between the two consecutive sound sensors. In this project, due to the fact that we need high accuracy, and also the length of the pipeline is long (185 km), the use of this method is not economical. The acoustic leak detection system works by changing the frequency of the sound. Hence, other sounds in the surrounding area can cover the noise caused by the leak. Besides, this method is not suitable for detecting small leaks having low noise levels. So, the acoustic system does not meet the requirements of this project.

- In vapor or liquid sensing tube technique, the leak detection speed is deficient, and this method is not suitable for large pipelines due to the high cost of equipment. Therefore, considering the long length of pipeline in this project, this system is not appropriate.

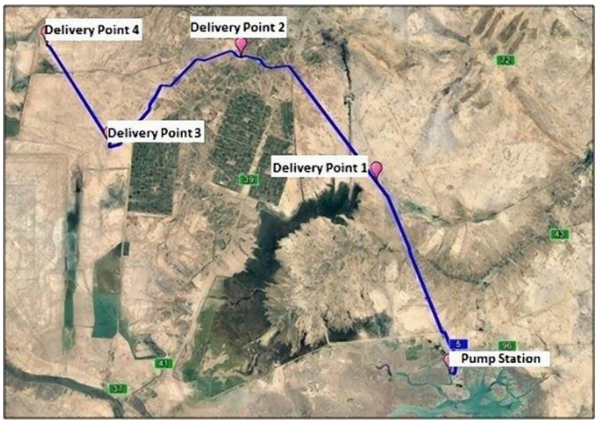

Fig. 8. Pipeline route from pump station to delivery points.

- The liquid sensing cable system, as the previous system, applies to short pipelines.
- The soil monitoring technique is costly because of the need for continuous injection of the detector. As a result, it is not appropriate for using in this project.
- The mass-volume balance method has many false alarms in unsteady flow conditions. Also, it cannot determine the location of the leak. This is one of the critical factors in choosing a leak detection system in this project.
- The real-time transient modeling (RTTM) system has low false alarms and quick leak detection, but its locating error is 1 % to 2 % of the length of the pipeline. So, where the length of the pipeline is about 185 km, this error is too high, and the method is not applicable.
- Negative pressure wave method is not practical for leak detection in long pipelines. This method is only effective for large instantaneous leaks.
- The basis of leak detection in the pressure point analysis system is the measurement of the drop in pressure value, so there might be many false alarms. In this project, the valves used along the line can cause a drop in pressure values, so this method is not recommended.
- In the statistical system, the noise in the surrounding area can interfere with statistical data, and the system cannot detect all leaks. Also, in this method, the visible leaks are just detectable.
- Digital signal processing system, like the statistical system, is not applicable in detecting small leaks, and it is difficult and expensive to implement, so it is not acceptable in this project.
- The fiber optic sensors system has the ability to identify tiny leaks (micro leaks), and also its leak detection time is less than one minute. Due to the operation type of this system, the number of false alarms is very small, and the leakage point's localization error is less than 1.0 meter.

4. Conclusions

As a consequence, the most suitable method for detecting leak in a long saltwater transmission pipeline, which requires high accuracy and short time for detecting in terms of environmental considerations, is the fiber optic method. Table 1 shows the specifications of this system.

Table 1. Fiber optic sensor specifications.

Index	Fiber optic sensor
Sensitivity	Ability to detect the very small leak (micro leak)
Leak detection time	Less than a minute
Reliability	Very few false alarms (less than two times a year)
Maintenance	Need to maintain and repair cables
Accuracy	Less than 1.0m

The distributed fiber optic monitoring system creates a continuous monitoring of pipes, improving their safety, and enabling the pipe operator to be informed and make proper decisions on the operations and maintenance of the pipe. In specific, this system allows the following monitoring functions (Glisic and Inandi. 2007):

- Distributed Temperature Monitoring

Allows the measure of the temperature distribution along the pipeline. This information is used for optimizing operational parameters.

- Leakage Detecting

During the detection of temperature disturbance, it is possible to identify small leaks that cannot be identified by conventional volumetric methods. In addition, the ability to localize the accurate place of the leakage enables an immediate response at this place, reducing downtime and ecological results.

- Intrusion Detecting

Based on a same method, concentrating on localized strain and temperature variations, the existence and place of an accidental intrusion can be identified. This allows preventive action before the intruder can damage the pipe.

- Distributed Strain and Deformation Monitoring

This provides information about the strain variation along the pipe. This is exclusively helpful at crucial places where movements caused by natural changes, such as earthquakes, or human actions can introduce potentially dangerous strain conditions to the pipe. In addition, this approach has the ability of detecting wall-thickness variations along the pipeline, because of corrosion or erosion. The features and applications of the fiber optic system are summarized in Table 2.

Table 2. The features and applications of the fiber optic system.

Features	Applications
Distributed measurement of strain & temperature	Pipeline leak detection
High spatial resolution	Strain or curvature monitoring of pipeline
Extended range	Water industry / water pipelines
Long-term stability	Oil & gas pipelines
Transportable system	Coal mining
Single-fiber, single-end or loop operation	Slope stability Dam seepage monitoring
Cost effective for large no. of measurement points	Road & rail strain and settlement
Intrinsically safe	Structural monitoring

Recent advances in fiber-optic technology make it possible to monitor more than 60km of line length with just one measuring device. This length can be extended up to 300km using optical amplifiers. Pipeline monitoring can prevent fracture and detect the exact location in the event of a fault, and also optimize maintenance programs. As a result, with the use of this system along the pipelines of this project, with the increase of safety, the operating costs will be optimized, and the waste of economic resources will reduce. For the future studies, it is recommended to implement a pilot to compare the real results with the fiber optic method characteristics.

Nomenclature

FBG	Fiber Bragg Grating
LDS	Leak Detection System
NPW	Negative Pressure Wave
RTTM	Real-Time Transient Modeling

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