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Studies on Distributed Brillouin Scattering Technique for Monitoring of Lifeline Structures

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Pipeline networks are the most efficient means for transporting large quantities of oil and gas through large distances. These pipelines cross different geographical terrains and are subjected to different manmade and natural hazards. Also these pipelines are prone to failures due to aging. Leakage in pipelines, particularly those carrying fuels is very dangerous as it leads to environmental pollution and also fatal accidents. The pipeline infrastructure industry has seen extensive growth in the recent years and hence there is a huge necessity for the development of real time pipeline monitoring technologies for reliable and safe operation of pipeline networks. Presently, health assessment and real time monitoring is gaining popularity among the researchers as it provides quality information on the performance of complex systems during its operation. There are different types of technologies developed for real time monitoring of pipelines using distributed fiber optic sensors, acoustic emission techniques and guided wave techniques. This paper presents in detail the theory of brillouin based distributed optical fiber sensing technology and studies carried out using the distributed fiber sensing for monitoring strain and temperature profiles through laboratory experimental investigations. Experimental investigations were carried out by simulating leakage in pipelines filled with hot water to study the performance of the distributed fiber sensors. Leakage was simulated in pipelines by drilling small holes at predetermined locations. Detection time was from 5 to 10 minutes and location of leakage was exactly detected with the spatial resolution of 80 mm. Brillouin based distributed fiber sensing system is a promising technique for monitoring long distance pipelines.

Keywords: Brillouin Scattering, Distributed fiber sensing, Leakage detection, Pipelines, Temperature

Introduction

Pipelines play a major role in transporting huge quantities of oil, gas and water for long distances. There are different categories of pipeline systems including piping systems in major industrial plants and cross country pipelines that run through several countries in the world.[1,2] The pipeline networks are the most efficient means for transporting large quantities of oil and gas through large distances.[3,4] These pipelines cross different geographical terrains and are subjected to natural hazards such as earthquakes and landslides. Also these pipelines are prone to manmade hazards such as intrusion, vandalism and other infrastructure activities.[5] Further due to continuous operation, these pipelines are susceptible to additional wear and tear. The operation of these pipelines are also affected by corrosion and aging. Corrosion of the pipeline leads to the reduction of pipeline wall thickness and thereby inducing leakage in the pipeline.[6] Leakage in pipelines, particularly those carrying fuels is very dangerous as it leads to environmental pollution and also fatal accidents. In addition to corrosion, many factors such as intrusion and external impacts cause leakage in pipelines.[7] It can be seen that leakage in the pipelines cannot be avoided as it is caused due to variety of conditions. However, the frequency of such leakages or accidents can be minimized through real time monitoring of the pipelines during it operation. Through real time monitoring, leaks can be detected immediately and remedial actions can be started quickly to minimize the losses. Hence it reduces the loss rate, fatalities, environmental pollution and other effects of leakage.[8] The pipeline infrastructure industry has seen extensive growth in the recent years and hence there is a huge necessity for the development of real time pipeline monitoring technologies for reliable and safe operation of pipeline networks. Conventional condition assessment of pipeline is carried out through intelligent pigging or by using pipeline inspection robots. But these periodical inspection methods does not provide the condition of the pipeline at real time and mostly these are suitable for assessing the integrity of the pipelines at a particular point of time.[9,10] Detection of leakage

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along the pipeline network is an essential part of the maintenance activity which is always a difficult task. Presently, health assessment and real time monitoring is gaining popularity among the researchers as it provides quality information on the performance of complex systems during its operation. Integrated health monitoring comprising of latest sensor and communication technology can improve overall performance of the underground system during the service life. There are different types of technologies developed for real time monitoring of pipelines using distributed fiber optic sensors, acoustic emission techniques and guided wave techniques.[11–13]

In the recent years, fiber optic sensors have been widely used for real time health monitoring applications.[14–16] Optical sensors are suitable for long term monitoring applications and are more reliable compared with other conventional electrical resistance based sensors. The main advantage of these optical sensors over electrical resistance based sensors is self-referencing and immune to electromagnetic interference. These sensors have the advantage of multiplexing, where many sensors can be connected to a single optical channel. These sensors can be suitably protected and can be installed in any kind of system during its commissioning.[17] A lot of applications for monitoring various engineering structures using optical fiber sensor-based systems have been reported.[18] The optical fiber sensors are sensitive to various mechanical parameters such as strain, temperature, acceleration, displacement and cracks. Fibre optic sensors offer a relatively new technology for the monitoring and evaluation of pipeline integrity and performance.[19]

Based on the mode of sensing, the fiber optic sensors are classified into localized sensing and distributed sensing. In localized sensing, several point sensors can be multiplexed to a single fiber optic cable for measuring various parameters at the vicinity of the point sensor. In distributed sensing, temperature and strain variations are measured along the entire length of the optical fiber through scattering of light. Several studies have been reported in the last decades on the development and application of distributed sensing for real time monitoring applications.[20,21] Investigations on application of distributed fiber technology, identification and selection of suitable sensors using fiber optic sensing technology for pipelines were reported elsewhere.[22–25] The distributed sensors are used for monitoring global variations rather than local variations and hence more suitable for identifying the location of leakage.[26] Due to the leakage of oil or gas from the pipeline, there will be variation of ambient conditions of the surrounding soil. The location of leakage in pipeline can be identified by measuring the variation of ambient conditions of soil using distributed fiber sensing.[27] Studies were also reported on application of distributed sensing for identifying corrosion and leakage in pipelines.[28] The distributed optical fiber sensing has better accuracy in locating the defects along longer lengths and is well suitable for long running systems like pipelines.[29–30] It can be seen that several studies have been reported globally on pipeline monitoring using distributed fiber sensing technique. In India, pipeline monitoring using distributed sensing is still under development. This paper presents in detail the theory of brillouin based distributed optical fiber sensing technology and studies carried out using the distributed fiber sensing for monitoring strain and temperature profiles through laboratory experimental investigations. The main aim of this paper is to help researchers and practitioners to gain insight on distributed sensing technologies, and its application for field problems.

Distributed Fiber Optic Sensors

A typical glass optical fiber is made from silica and it is used for transmitting light for large distance using internal reflection without any losses. Any optical fiber consists of a core, cladding and a protective coating. The light is transmitted inside the core and the core is supported by a cladding for minimizing the losses during transmission of light. A protective coating usually made of either polymide or acrylic is present over the cladding to give mechanical strength to the optical fiber as it is very fragile. The protective coating is chosen based upon the application and compatibility with the specimen material during measurement of strain. The protective coating makes the bare optical fiber to be suitable for practical applications and harsh environment. Conventional electrical resistance based strain sensors are suitable for local variations owing to their short gage length. The fiber optic sensor overcome this through long gage sensors and distributed sensors. Long gage discrete fiber optic sensors can be used for monitoring strain variations for longer lengths or for global variations. Typical long gage fiber optic sensors are made as Bragg gratings that have different grating lengths suitable for strain and temperature monitoring.

A distributed fiber optic sensor is sensitive to both strain and temperature variations at any point along the entire fiber length. Hence a single distributed optical fiber sensor can replace thousands of discrete short gage point sensors.[31] These distributed optical fiber sensors gives the variation of measurands such as strain and temperature as a function of their location along the length of the optical fiber and magnitude of the variation is obtained using the shift in the measured wavelength. Thus by using the distributed optical fiber sensing the magnitude of the variation and also the exact location of the variations is obtained. Also these sensors require only one cable to be connected to the data acquisition system whereas the conventional sensors require distinct cables for each sensor to be connected to the data acquisition system.

Scattering of Light inside Optical Fiber

Distributed fiber optic sensors are sensitive to physical parameters such as strain and temperature along the entire length of the fiber. The principle behind the working of the distributed sensor is based on the scattering of light inside the optical fiber. A light with known wavelength is pumped into an optical fiber. The pumped light travels through the length of the fiber whereas a part of the light is reflected back along the fiber. There are three types of scattering inside the optical fiber namely Rayleigh scattering, Brillouin scattering and Raman scattering.[32–34] Each scattering gives information on various physical parameters. Rayleigh scattering gives information on the acoustic vibrations along the length of the fiber. Brillouin scattered light gives us the information on strain and temperature variations along the length of the fiber. Raman scattering is used for the measurement of temperature variations along the length of the optical fiber. These scattering causes shift in the frequencies which is dependent on strain and temperature variations. The various scattering that occurs in an optical fiber is shown in Fig. 1. It can be seen that Brillouin scattering is dependent on strain and temperature variation whereas Raman scattering is dependent only on temperature variations alone. Raman scattering occurs at around 13 THz from Rayleigh signal whereas Brillouin scattering occurs at around 11 GHz.

Rayleigh scattering effect is used for measuring both strain and temperature variations along the length of the fiber based on the shifts in the back scattered light which carried the information of the physical parameter and location. There is no shift in the frequency of the Rayleigh scattered light and it depends on the material characteristics of the optical fiber. Optical Time Domain Reflectometer (OTDR) system is based on the Rayleigh scattering principle. Normal glass fibers are not suitable for obtaining Rayleigh scattering and liquid cooled fibers are required for the measurements. Mostly Rayleigh back scattering is mainly used for distributed acoustic sensing by using the phase change in the backscattered light through Phase-OTDR technique.

Brillouin scattering occurs in an optical fiber due to the interaction of the light with thermally excited acoustic phonons. Brillouin scattering is also used for obtaining the variation of strain and temperature along the length of the optical fiber based on the shift in the frequency of scattered light. Since these techniques are used for measuring the strain over longer distances, the effect of temperature in measuring strain has to be considered. Hence the strain should be compensated for temperature. The optical sensors used for temperature measurements will have loose optical fibers meant for only temperature measurements. There are two types of systems for measuring the strain and temperature variation 1) Brillouin Optical Time Domain Reflectometry (BOTDR) where only one end of the optical fiber is connected to the system and is based on spontaneous Brillouin Scattering 2) Brillouin Optical Time Domain Analysis (BOTDA) where both the ends of the optical fiber is connected to the system and it is based on stimulated Brillouin scattering. Practically BOTDR is easy for installation as only one end of the optical fiber has to be connected to the system whereas BOTDA can be used for higher sensing ranges. In BOTDA, light is sent through both ends of

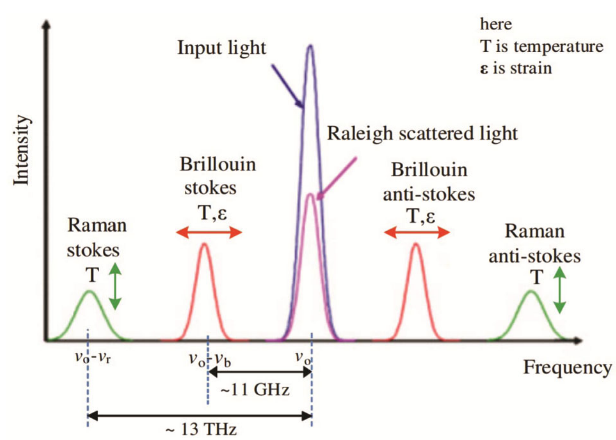

Fig. 1 — Scattering of light in an optical fiber[35]

the fiber as pump and probe signal (Fig. 2). Hence the backscattered signal will have improved strength and gives higher accuracy for strain and temperature measurements. The Brillouin frequency shift varies linearly with respect to the physical parameters such as strain and temperature. Hence the frequency shift is correlated to the physical parameters. The Brillouin frequency shift with respect to that of the pump frequency is given by the relation.[36]

Brillouin Frequency Shift, $V_B = (2nV_a)/\ \lambda_p$ and $V_a = \sqrt{(K/\rho)}$ … (1)

where n is the refractive index, V_a is the acoustic velocity and λp is the pump wavelength, K is the bulk module and ρ is the density of the optical fiber.

Raman scattering occurs in the optical fibers due to the interaction of incident light transmitted in the fiber with the material of the fiber due to molecular vibrations. By transmitting a light through the optical fiber, two frequency shifted components will appear in the back scattered light called as stokes and anti-stokes. The anti-stokes component is influenced by the temperature variations in the optical fiber. Hence systems based on Raman scattering technique acquires the relevant frequencies and the ratio between the two components of the back scattered light to obtain information on the temperature variations along the fiber. Raman scattering systems requires multi mode optical fibers and also due to attenuation of light in the multi mode fibers the length of sensing fiber limits to approximately 8 to 10 km.

Temperature Measurements using BOTDA

Preliminary calibration studies were carried out to understand the response of the distributed fiber sensor to known temperature variations. The calibration test setup is as shown in Fig. 3. A vessel was filled with hot water having a temperature of around 80°C. The optical fiber was connected to the interrogator in BOTDA mode (both the ends were connected to interrogator). It is a single mode optical loose fiber packed inside a protective tube suitable for temperature measurements alone. The fiber is in unrestrained condition so that the frequency shifts are due to temperature variations only. Baseline frequency of the optical fiber measured at ambient temperature of 30°C prior to the experimental program was 10880 MHz. A small portion of the optical fiber was placed in the vessel with hot water. The temperature of the hot water was also monitored using a temperature sensor for validation with the distributed sensor. The brillouin frequency was measured at frequent intervals during the experimental program.

The measured frequency shift is converted into temperature using the fiber temperature coefficient 0.9765MHz/°C. The absolute temperature of the water was also measured using a temperature sensor which was around 80°C. The difference between the baseline frequency and the measured frequency is plotted in Fig. 4. The shift in frequency is converted into temperature using the calibration coefficient of the fiber as per Eq. (2) and plotted as shown in Fig. 5.

$V_B\ (\varepsilon, T) - V_B\ (\varepsilon_0, T_0) = C\varepsilon \times \delta\varepsilon + C_T \times \delta T$ … (2)

where V_B (ε, T) is the Brillouin frequency due to strain and temperature in the optical fiber andV_B (ε_0, T_0) is the baseline Brillouin frequency of the optical fiber before subjecting the optical fiber to strain and temperature variations at ambient conditions. C_ε and C_T are the coefficients of optical fiber for strain and temperature respectively. δε and δT are change in strain and temperature respectively. From the plot it can be seen that the measured temperature was around 41.14°C. The room temperature during the measurement of baseline frequency was around 30°C.

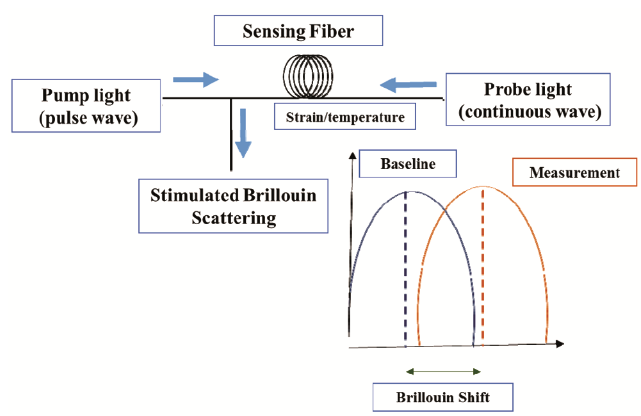

Fig. 2 — Stimulated Brillouin scattering inside optical fiber

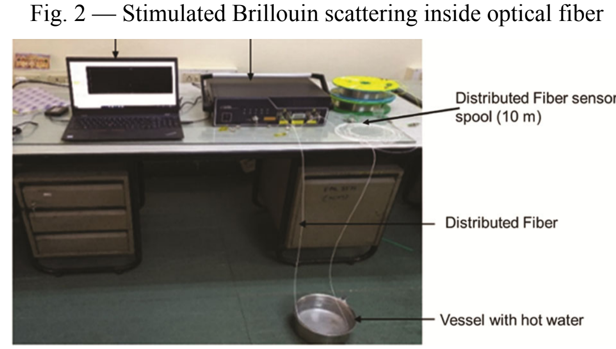

Fig. 3 — Temperature calibration of optical fiber

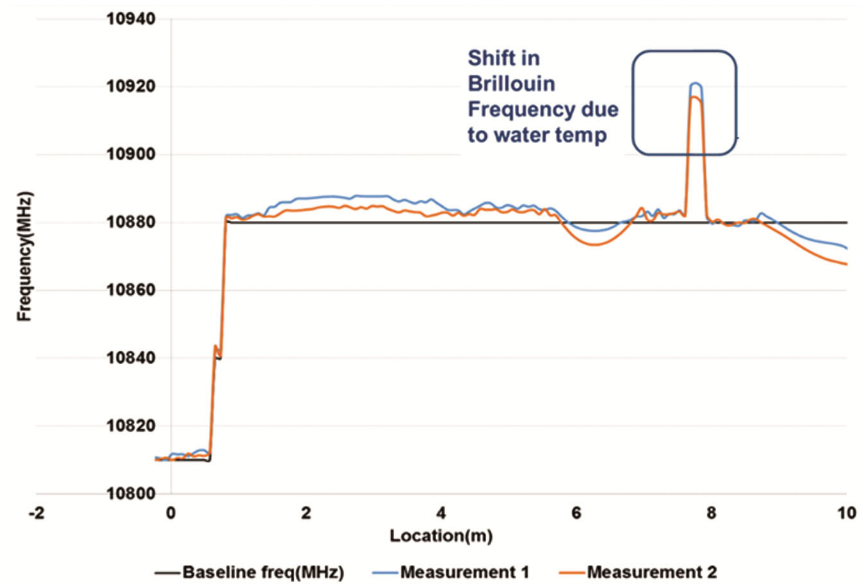

Fig. 4 — Brillouin frequency shift due to temperature variation

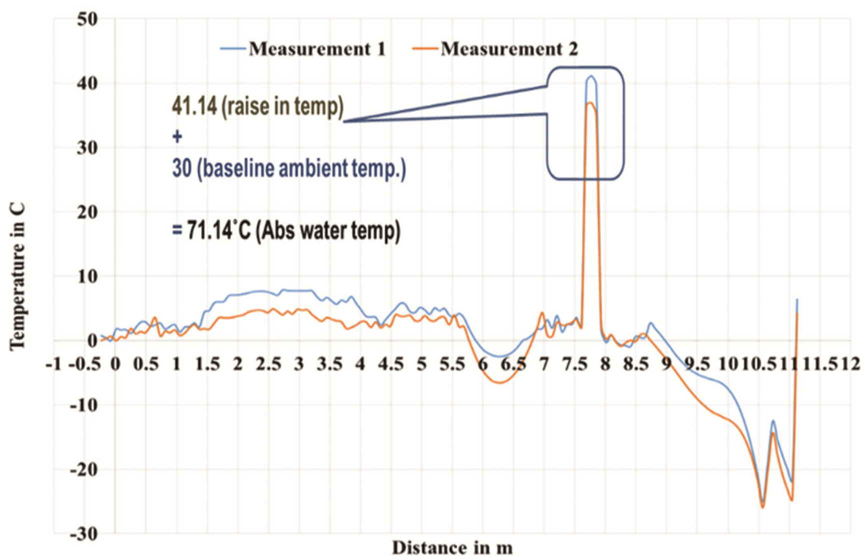

Fig. 5 — Temperature variation measured using Brillouin scattering

Hence the absolute temperature measured was 71.14°C. Thus the optical fiber sensor is sensitive to temperature variations and also gives variation of temperature profile along the length of the fiber.

Pipeline Leakage Detection using Stimulated Brillouin Scattering

Stimulated Brillouin scattering is sensitive to temperature and strain variations along the length of the optical fiber. This property is used for monitoring the leakage in pipelines using fiber optic sensors along the length of the pipelines. The scattering will give information on the temperature variation along with the location of change. Since the leakage location can also be identified in long distance running pipelines, Brillouin scattering based fiber optic sensing is very much suitable for leakage monitoring in buried pipelines. When there is a leakage in the pipeline at any location in the pipeline network, the spilling of oil or gas will result in a change in the ambient temperature in the surrounding soil based on the Joule Thompson effect. Since all the fuels transmitted through pipelines are under pressure, there will be a distinct temperature difference with respect to the surrounding soil. This change in temperature is sensed by the optical fiber instrumented near the pipeline and gives us the information of onset of leak in the pipeline along with the location of leak point. However the sensitivity of the system depends upon several factors like the temperature difference between the surrounding soil and that of the fuel inside the pipeline, properties of the surrounding soil, permeability of the soil, location of the sensor away from the pipeline and quantity of leakage. In case of pipelines carrying oil, the best location for placement of the optical fiber is below the pipeline as the leakage will cause the oil to flow downwards, whereas in case of gas pipeline, it is better to place the optical fiber above the pipeline.

Experimental investigations were carried out using a PVC pipeline model by simulating leakage in predetermined points. The pipeline was buried inside a soil to simulate the field conditions. Two distributed optical sensors were laid on the soil at a depth of 100 mm from the bottom of the pipeline. Holes were drilled in the pipeline to induce leakage of water. A layer of soil was put over the installed fiber and the pipeline was placed firmly. Again soil was filled on top of the pipeline and it was buried. The experimental investigations were carried out using hot water for inducing significant temperature variations. The optical fiber sensor was connected in BOTDA mode. Both ends of the optical fiber were connected to the data acquisition system. The experimental test setup is shown in Fig. 6 and the data acquisition system in BOTDA is shown in Fig. 7. The spatial resolution of the distributed sensor was kept at 80 mm with 10 ns pulse width. The fiber length of around 10 m was instrumented in the soil. It is a single mode optical loose fiber packed inside a protective tube suitable for temperature measurements alone. The fiber is in unrestrained condition so that the frequency shifts are due to temperature variations only. Baseline frequency of the optical fiber measured at ambient temperature of 32°C prior to the experimental program was 10800 MHz. Fiber strain coefficient and fiber temperature coefficient is about 18.9150MHz/με and 0.9765MHz/°C respectively.

A FBG based fiber optic based temperature sensor was instrumented inside the pipeline for measuring the temperature of the water. The pipeline was filled with hot water. Due to the holes in the pipeline, there will be leakage of hot water from the pipeline. The Brillouin frequency of the optical fiber was measured at frequent intervals after filling with hot water. The baseline frequency measured prior to the experimental program is plotted along with the frequency measured after filling the pipeline with hot water is shown in Fig. 8. It can be seen from the plot that, the Brillouin frequency shift has been seen only at those three points where leakage has been simulated. Due to leakage in the pipelines, there will be change in the temperature of the surrounding soil. Hence by using these distributed optical fiber sensors, the leakage can be identified along with the location of leakage. The measured frequency shift is converted into temperature using the fiber coefficient as 42.46°C. The ambient temperature during measurement of baseline frequency was 32°C. Absolute temperature of water measured using FBG temperature sensor in the pipeline is 84°C. Hence the absolute temperature measured using distributed optical sensor in soil at a depth of 100 mm is around 74.46°C. To summarize, experimental investigations were carried out by simulating leakage in pipelines filled with hot water to study the performance of the distributed fiber sensors. Leakage was simulated in pipelines by drilling small holes at predetermined locations.

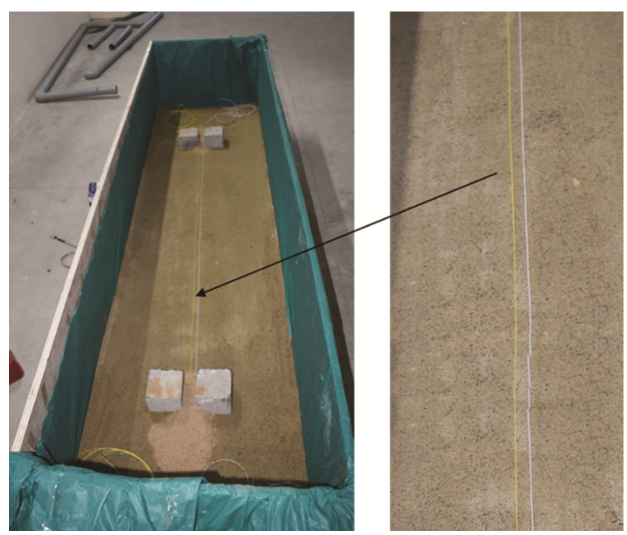

Fig. 6 — Distributed fiber optic sensor for leakage monitoring

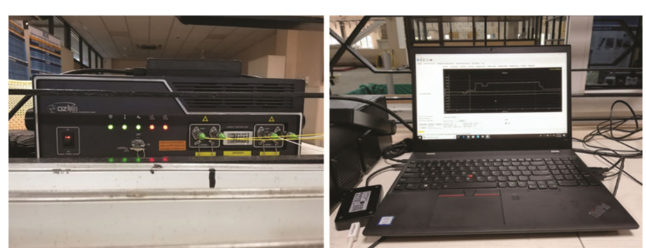

Fig. 7 — Data acquisition system in BOTDA mode

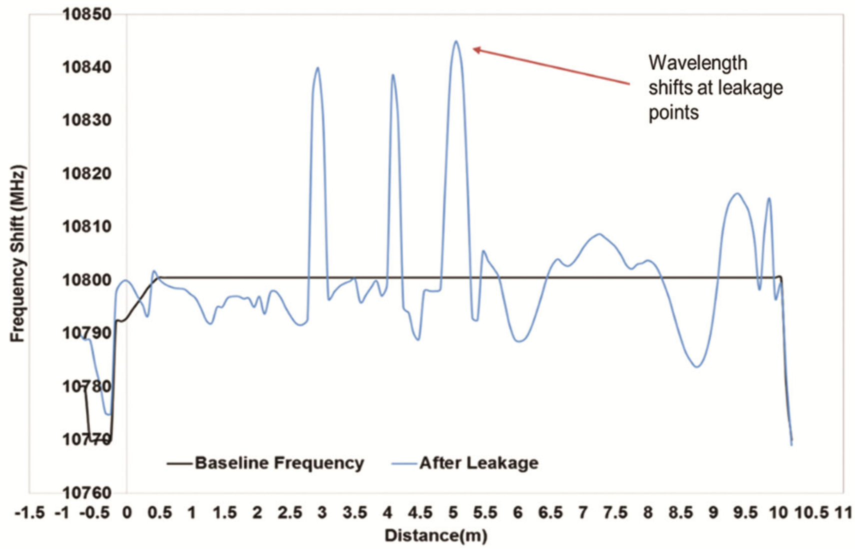

Fig. 8 — Brillouin frequency shift due to leakage in pipeline

Detection time was from 5 to 10 minutes and location of leakage was exactly detected with the spatial resolution of 80 mm. Since the temperature difference between the water and the surrounding soil is high the detection time was very less. Also the detection time depends upon the permeability of soil and the volume of leakage. It also depends on the location of the sensor from the pipeline and the temperature difference between the surrounding soil and the medium transported in the pipeline.

Summary and Conclusions

Detection of leakage along the pipeline network is an essential part of the maintenance activity which is always a difficult task. From the preliminary temperature calibration studies, it can be seen that the measured temperature was around 41.14°C. The room temperature during the measurement of baseline frequency was around 30°C. Hence, the absolute temperature measured was 71.14°C. The measured frequency shift is converted into temperature using the fiber coefficient as 42.46°C. The ambient temperature during measurement of baseline frequency was 32°C. Absolute temperature of water measured using FBG temperature sensor in the pipeline is 84°C. Hence, the absolute temperature measured using distributed optical sensor in soil at a depth of 100 mm is around 74.46°C. From the reported studies it can be seen that the temperature variation can be obtained along the length of the optical fiber and with respect to the length. Based on the spatial resolution the temperature is obtained at each point of the optical fiber. Through the experimental investigations it can be seen that leakages can be identified and localized using the distributed fiber optic sensing by measuring the temperature variations. However, the detection time depends on various parameters such as permeability of surrounding soil, temperature difference between the pipeline fuel and surrounding soil, quantity of leakage etc. Brillouin based distributed fiber sensing system is a promising technique for monitoring long distance pipelines. However, further detailed studies are being carried outtowards developing techniques to monitor long range oil and gas pipelines using distributed fiber sensing.

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