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Experimental and numerical investigation on temperature measurement of BOTDA due to drop leakage in soil

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ABSTRACT

Using an advanced Brillouin sensing system (BOTDA) with high spatial resolution, this paper demonstrates the application of the distributed temperature fiber optic sensor (FOS) in small liquid leak detection in soil. The effectiveness and efficiency of the distributed Brillouin sensor in detecting and locating drop leakage in soil is qualitatively verified through a laboratory experiment. Numerical studies based on finite element (FE) method are conducted to simulate the whole drop leak process. The good agreement of the data measured in the experiment and the computational results validates the spatial distribution and the variation trend of the soil temperature field due to drop leakage. A quantitative relation between the active area of the leak-induced temperature field and the FOS measurements is established to determine the size of leak or to propose a FOS-based strategy for leak early warning.

1. Introduction

Pipelines, which have been acknowledged as “lifelines” for the transportation of fluids like water, oil and gas, play an important role in modern society. Leakage of pipelines may cause high economic losses, serious environmental problems and public safety threats. Early detection and precise location of leakage is of great importance for life-cycle maintenance and management of widely-distributed pipeline system.

Methods used to detect leakage along a pipeline are in general divided into two categories (Colombo et al., 2009), internally or externally based. Internally based methods, also known as computational pipeline monitoring (CPM) (API, 2002), usually monitor internal pipeline parameters (i.e., pressure, flow, temperature) and then use them as inputs to identify a potential leakage by manual or electronic computation. Although these parameters can be easily obtained, the reliability of the “inferential” methods is severely affected by the accuracy of the measured data. Moreover, it is difficult to determine the reason of abnormal measurements is due to pipeline leakage or operating condition. Externally based methods, on the contrary, can “directly” detect the leakage by means of manual efforts or online instruments. The traditional procedure is to conduct a right-of-way inspection by line patrols, which are laborious, time consuming and sometimes overlook the accidence occurring just after the periodic inspection. As a result, operators and researchers have been looking at new solutions for leakage detection through continuous pipeline monitoring technologies, such as acoustic emission (AE) detectors (Sinha, 2005; Ozevin and Harding, 2012), vapor or liquid sensing cables, and fiber optic sensors (FOSs) (Frings and Walk, 2010; Si and Lee, 2010; Nikles et al., 2004a).

In the past few years, innovative distributed temperature monitoring techniques using optical fibers have demonstrated to be a potential way to detect and locate leakages along pipelines given the fact that the fluid leakage may lead to the temperature variation in the vicinity of pipeline. Unlike electrical and point fiber optic sensors, truly distributed sensors offer the unique characteristic of being able to measure parameters of thousands of points along their whole length by the fiber itself as the sensing medium (Culshaw and Kersey, 2008). These techniques use a concept similar to optical domain reflectometry (OTDR) for the localization, whereas the temperature information is extracted from the analysis of the scattered light through Raman or Brillouin scattering processes. To achieve good effect in practical application in pipeline leak detection, the distributed fiber optic sensing techniques face two main challenges: (1) leakage usually starts from dripping at a slow speed and the area subjected to temperature variation is localized, while the spatial resolution and the measuring precision of these instruments are not good enough to catch the localized

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information especially in the case of slight leakage or tiny temperature change; (2) the knowledge of soil temperature field due to pipeline leakage and its corresponding relation with the measurements from the distributed FOSs is desired to propose an efficient strategy for leak early warning.

Regarding the first challenge, many fiber optic sensing systems have been developed and improved to acquire the high-quality distributed temperature measurements over the past decade. One class of them is based on Raman scattering and referred to as ROTDR (Kher et al., 2002), in which short laser pulses are launched into the optical fiber to generate Raman anti-Stokes (AS) and Stokes (St) signals. The ratio of AS intensity to St intensity is measured and then used to determine the absolute temperature. To obtain the temperature profile with certain accuracy for complete fiber length, a lot of appropriate measures have been devised and implemented to address specific error causing issues (Chakraborty et al., 2007; Suh and Lee, 2008; Saxena et al., 2015). Despite these efforts, Raman-based techniques, which rely on the measurement of signal intensity, inevitably suffer from a high sensitivity to drifts. By contrast, the frequency-based Brillouin sensing techniques are inherently more accurate and more stable on the long term. As a result, many research works have been devoted to the development of Brillouin sensing systems to acquire the Brillouin frequency shift (Culshaw and Kersey, 2008). One kind of them is based on the Brillouin loss technique (Shimizu et al., 1994; Koyamada and Sakairiet a1., 2007; Yan and Chyan, 2010), whereby two counter propagating laser beams, a pulsed Stokes beam and a continuous wave (cw) pump beam, exchange energy through an induced acoustic field. A loss signal can be then detected and used to determine the Brillouin frequency shift, which has a linear relation with the temperature variation. The distributed Brillouin loss sensor can measure, in principle, the temperature at any point along the sensing fiber. The spatial resolution is determined by the speed of light in vacuum, the refractive index of fiber core, and the Stokes pulse width. Although the spatial resolution can be improved by use of short pulses, the loss spectrum broadens and the amplitude of the spectrum decreases as the pulse width decreases below the phonon lifetime of 10 ns,, which makes it difficult to measure the Brillouin frequency shift accurately and results in a 1-m spatial resolution limitation. Regarding this, a probe-pump Brillouin sensing system by using a combination of cw and pulsed light as the probe beam and a cw laser as the pump beam has been presented recently, which demonstrates that a spatial resolution of 100 mm can be achieved (Zou et al., 2004; Dong et al., 2009; Bao and Chen, 2011).

On the other hand, to verify the effectiveness of the advanced distributed FOSs in pipeline leak detection, field tests (Nikles et al., 2004b; Inaudi and Glisic, 2010) have been conducted to investigate the actual responses of optical fibers to soil temperature variation due to leakage. Unfortunately limited by the test conditions, the derived results are usually case dependent and qualitatively evaluated. Considering the high cost for experimental case studies, numerical simulations have become a better alternative. The soil temperature field due to pipeline leakage under a certain condition can be numerically investigated, based on which threshold values are then set for early warning regarding specific monitoring targets. However, most of the current literature focus on the leak simulation of the buried pipelines of high pressure (Mirzaei et al., 2013; Bhuiyan et al., 2016). Very few works are reported with respect to small drop leakage, which is a more crucial stage for early warning.

By using an advanced Brillouin sensing system with high spatial resolution, this paper demonstrates the application of the distributed fiber optic sensor in small water leak detection in soil. Experimental and numerical investigations are conducted to explore the spatial distribution and the developing trend of the soil temperature field due to drop leakage, based on which the capability and adaptability of the fiber optic sensor in small leak detection are validated.

2. Experiments of water leak detection

Based on the unique coherent probe-pump interaction technique, a high-performance Brillouin sensing system (BOTDA) has been developed and reported to achieve the spatial resolution of 100mm[16], which is a significant improvement by comparing with the conventional resolution of 1 m. The calibration tests have demonstrated that the system using the spatial resolution of 0.5 m and the sampling interval of 0.05 m is the optimal option to achieve stable temperature measurements at the rate of once per minute (Han and Li, 2013). In this section, laboratory experiments are designed and conducted to acquire the actual responses of the optical fiber to the soil temperature variation due to water drop leakage by employing the BOTDA system.

2.1. Experimental set-up and procedure

To represent liquid drop leakage of underground pipeline, a simplified set-up is designed, as shown in Fig. 1. A soil bin of about 1 m length and 0.2 m width is put up, filled in roughly 3 cm thick soil. Leakage is simulated by the water dripping down from a faucet, which is connected to a water container via an adjustable valve. Although a realistic buried pipeline is not involved here, this set-up is sufficiently representative to verify the effectiveness of small leakage detection in soil for the reasons that: (1) Generally, the temperature variation due to a real leakage in a buried pipe with good thermal insulation qualities is quicker and more evident than that due to the water drop from a hanging "faucet" because the leaked water directly goes into the soil and takes into effects immediately; (2) The difference of the experimental tests from real applications only lies in that the hot water starts from the surface rather than the inside of the soil, which is more difficult for temperature sensing. Two kinds of sensors are buried 1 cm below the soil surface for temperature measurements: distributed fiber optic sensor (FOS) and six temperature sensitive resistors (TSRs, T1 ~ T6).

The experiment starts from water dripping at a slow speed at 12:25 pm. The room temperature is about 24 °C. The temperature of the water inside container is kept around 40 °C and decreases to 30 °C at the moment the water drops to the soil surface. The water-dropping point is between T3 and T4, about 4 cm away from T4. The whole process of water dripping lasts almost 40 min. Data is recorded every minute. The spatial resolution and the sampling interval of BOTDA are set to be 0.5 m and 0.05 m, respectively. While the total fiber length is 408 m, the concerned sensing part buried to the soil bin is about 1.5 m, which is within the coordinate range from 15 m to 18 m.

2.2. Temperature measurements

To analyze the variation tendency of soil temperature measurements over time, the experimental process is artificially divided into two stages (see Table 1): (1) Stage I for the early stage of water dripping; (2) Stage II for the late stage of water dripping. The data before water dripping (12:25 pm) is recorded to set a baseline and all the following results are presented as the changes by comparing with it.

The temperatures measured by the two types of sensors at stage I can be found in Fig. 2. At the beginning of the experiment (12:25 pm), all the measurements change little from the baseline. After 1 min (12:26 pm), FOS presents a distinct peak at the location of 15.85 m and the change of temperature is about 1 °C. By now, the