Technology Status Report

on

Natural Gas Leak Detection in Pipelines

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U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road, P. O. Box 880
Morgantown, WV 26507-0880

by

Yudaya Sivathanu
En'Urga Inc.
1291-A, Cumberland Avenue
West Lafayette, IN 47906

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Distribution:
Attn: Daniel Driscoll, NETL
Jongmook Lim, En'Urga Inc.
Vinoo Narayanan, En'Urga Inc.

En'Urga Inc.

ANALYSIS OF COMBUSTION SYSTEMS

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1.0 Introduction

Natural gas consumption in the US is expected to increase 50% within the next 20 years (Anderson and Driscoll, 2000). At the same time, the gas delivery infrastructure is rapidly aging. The Department of Energy has stated that ensuring natural gas infrastructure reliability is one of the critical needs for the energy sector. The largest component of the natural gas infrastructure is the approximately 400 thousand miles of delivery pipelines. Therefore, the reliable and timely detection of failure of any part of the pipeline is critical to ensure the reliability of the natural gas infrastructure. This report reviews the current status of the technology for leak detection from the natural gas pipelines. The first part briefly reviews various leak detection methods used in the natural gas pipelines. The second part reviews the optical methods used for natural gas leak detection, and the final part reviews the potential sensors that can be used with optical methods.

2.0 Review of Leak Detection Methods

There are a variety of methods that can detect natural gas pipe line leaks, ranging from manual inspection using trained dogs to advanced satellite based hyperspectral imaging (Carlson, 1993; Scott and Barrufet, 2003). The various methods can be classified into non-optical and optical methods. The primary non-optical methods include acoustic monitoring (Hough, 1988; Klein, 1993); gas sampling (Sperl, 1991), soil monitoring (Tracer Research Corporation, 2003), flow monitoring (Turner, 1991; Bose and Olson, 1993), and software based dynamic modeling (Griebenow and Mears, 1988; Liou and Tain, 1994).

Acoustic monitoring techniques typically utilize acoustic emission sensors to detect leaks based on changes in the background noise pattern. The advantages of the system include detection of the location of the leaks as well as non-interference with the operation of the pipelines. In addition, they are easily ported to various sizes of pipes. However, a large number of acoustic sensors is required to monitor an extended range of pipelines. The technology is also unable to detect small leaks that do not produce acoustic emissions at levels substantially higher than the background noise. Attempts to detect small leaks can result in many false alarms.

Gas sampling methods typically use a flame ionization detector housed in a hand held or vehicle mounted probe to detect methane or ethane. The primary advantage of gas sampling methods is that they are very sensitive to very small concentrations of gases. Therefore, even very tiny leaks can be detected using gas sampling methods. The technique is also immune to false alarms. The disadvantages of the technology are that detection is very slow and limited to the local area from which the gas is drawn into the probe for analysis. Therefore the cost of monitoring long pipelines using gas sampling methods is very high.

In soil monitoring methods, the pipeline is first inoculated with a small amount of tracer chemical. This tracer chemical will seep out of the pipe in the event of a leak. This is detected by dragging an instrument along the surface above the pipeline. The advantages of the method include very low false alarms, and high sensitivity. However, the method is very expensive for monitoring since trace chemicals have to be continuously added to the natural gas. In addition, it cannot be used for detecting leaks from pipelines that are exposed.

Flow monitoring devices measure the rate of change of pressure or the mass flow at different sections of the pipeline. If the rate of change of pressure or the mass flow at two locations in the pipe differs significantly, it could indicate a potential leak. The major advantages of the system include the low cost of the system as well as non-interference with the operation of the pipeline. The two disadvantages of the system include the inability to pinpoint the leak location, and the high rate of false alarms.

Software based dynamic modeling monitors various flow parameters at different locations along the pipeline. These flow parameters are then included in a model to determine the presence of natural gas leaks in the pipeline. The major advantages of the system include its ability to monitor continuously, and non-interference with pipeline operations. However, dynamic modeling methods have a high rate of false alarms and are expensive for monitoring large network of pipes.

3.0 Review of Optical Methods

Optical methods of leak detection can be classified as either passive or active (Reichardt et al., 1999). Active methods illuminate the area above the pipeline with a laser or a broad band source. The absorption or scattering caused by natural gas molecules above the surface is monitored using an array of sensors at specific wavelengths. If there is significant absorption or scattering above a pipeline, then a leak is presumed to exist. The basic techniques for active monitoring techniques include Tunable Diode Laser Absorption Spectroscopy (TDLAS) (Hanson et al., 1980), Laser Induced Fluorescence (LIF) (Crosley and Smith, 1983), Coherent Anti-Raman Spectroscopy (CARS) (Eckbreth et al., 1979), Fourier Transform Infrared Spectroscopy (FTIR) (Best et al., 1991), and evanescent sensing (Culshaw and Dakin, 1996).

Active monitoring of natural gas leaks from pipelines has been achieved with Lidar systems, (Minato et al., 1999; Ikuta et al., 1999), diode laser absorption (Iseki et al., 2000), Millimeter Wave Radar systems (Gopalasami and Raptis, 2001), backscatter imaging (Kulp et al., 1993), broad band absorption (Spaeth and O'Brien, 2003), and evanescent sensing (Tapanes, 2003).

Lidar systems typically use a pulsed laser as the illuminating source. The absorption of the energy of the laser along a long path length is monitored using a detector. Diode laser absorption uses the same technology with the crucial difference being that diode lasers are used instead of the more expensive pulsed lasers. If only a single wavelength is used, the system can be prone to false alarms since the laser can be absorbed equally well by dust particles.

Broad band absorption systems utilize low cost lamps as the source, significantly reducing the cost of the active system. In addition, monitoring is achieved at multiple wavelengths so that the system is less prone to false alarms.

For evanescent sensing, an optical fiber is buried along with the pipe. When natural gas escapes, the local changes in pressure or concentration causes a change in the transmission character of the optical fiber. This change in the transmission characteristics is monitored using lasers and optical detectors.

Millimeter wave radar systems obtain a radar signature above the natural gas pipelines. Since methane is much lighter than air, the density difference provides a signature that can be used as an indicator of a potential leak. Backscatter imaging utilizes a carbon-dioxide laser to illuminate the area above the pipeline. The natural gas scatters the laser light very strongly. This scattered signature is imaged using an infrared imager or an infrared detector in conjunction with a scanner.

All the active systems described above use a source and obtain either transmitted or scattered images to determine the presence of methane. These systems are can be mounted on moving vehicles, aircraft or on location. The advantages of these systems include capability to monitor over an extended range and ability to monitor leaks even in the absence of temperature differences between the gas and the surroundings. In addition, these techniques have high spatial resolution and sensitivity under specific conditions (Durao et al., 1992). The two disadvantages of the method are the high cost of implementation and the high incidences of false alarms. Typically, these systems also require a skilled operator, and cannot be used for unsupervised monitoring due to the safety issues involved with the operation of powerful lasers.

Passive monitoring of natural gas leaks is similar to active monitoring in many aspects. However, the major difference between active and passive techniques is that passive techniques do not require a source. Either the radiation emitted by the natural gas or the background radiation serves as the source. This makes passive systems less expensive in some respects. However, since a strong radiation source is not used, much more expensive detectors and imagers have to be used with passive systems.

The two major types of passive systems used for monitoring leaks from natural gas pipelines are thermal imaging (Weil, 1993; Kulp et al., 1998) and multi-wavelength imaging (Althouse and Chang, 1994, Bennet et al., 1995; Marinelli and Green, 1995, Smith et al., 1999).

Thermal imaging detects natural gas leaks from pipelines due to the differences in temperature between the natural gas and the immediate surroundings. This method can be used from moving vehicles, helicopters or portable systems and is able to cover several miles or hundreds of miles of pipeline per day. Usually, expensive thermal imagers are required to pick up the small temperature differential between the leaking natural gas and the surroundings. In addition, thermal imaging will not be effective if the temperature of the natural gas is not different from that of the surroundings.

Multi-wavelength or hyperspectral imaging can be accomplished either in absorption mode or in emission mode. For obtaining gas concentrations utilizing multi-wavelength emission, the gas temperatures have to be much higher than the surrounding air. Multi-wavelength emission measurements have been typically used in the past to obtain single point concentrations in hot combustion products (Sivathanu et al., 1991; Sivathanu and Gore, 1991).

Multi-wavelength absorption imaging utilizes the absorption of background radiation at multiple wavelengths to directly image the gas concentration, even in the absence of temperature gradients between the gas and the surrounding air. This technique has been used to monitor natural gas leaks in industrial settings very successfully. However, multi-wavelength or hyperspectral imaging typically utilizes very sensitive and expensive imagers.

The biggest advantage of passive techniques is that they can be used from ground, vehicle, aircraft, and even satellite platforms. Therefore, long sections of pipelines can be monitored for natural gas leaks relatively easily. In addition, multi-wavelength passive systems are relatively immune to false alarms, and can be utilized for remote monitoring without being constantly watched over.

The optimal method of monitoring large lengths of pipeline would be to utilize an array of ground based imagers. However, for passive infrared absorption, the detectors have to be very sensitive. In addition, for imaging applications, the basic infrared arrays are very expensive. This is the biggest disadvantage of these passive multi-wavelength and thermal imaging techniques.

4.0 Review of Sensors

Absorption spectroscopy in the infrared region of the spectrum is very sensitive to gas concentrations (Zhang and Cheng, 1986; Best et al., 1991). In addition, absorption spectroscopy in the infrared is a robust technique and a range of single point sensors is available in the market. For monitoring leaks over a long distance of pipeline, single point absorption measurements cannot be used very effectively, since the gas does not always escape directly above the center line of the pipes. Therefore, imaging of the absorption over a small area above the pipe is essential. To image absorption by hydrocarbon gases, infrared arrays are required since the major absorption occurs in mid infrared bands (Grosshandler, 1980).

Practical single element infrared detectors were developed during World War II by the German military from a lead salt compound (PbS). Over the past 25 years, the availability of high performance infrared detectors has spurred civilian applications. Today's detectors range in format from single element, uncooled detectors to specialized multi-spectral, staring arrays. There are two main classes of infrared detectors (thermal type and quantum type) with several types within each class. Thermal type infrared detectors include thermopiles, bolometers (Neikirk et al., 1984), and pneumatic and pyroelectric detectors. Pneumatic detectors utilize the expansion of a noble gas under incident radiation to vary the output of the detector. In Pyroelectric Detectors, an electric charge is generated on the surface of a crystal in accordance with the amount of temperature variation.

Quantum type detectors are further classified into intrinsic types and extrinsic types. Intrinsic type detectors have detection wavelength limits determined by their inherent energy gap and responsivity drops drastically when the wavelength limit is exceeded. Among them, the photoconductive detectors, which change their conductivity when infrared radiation is incident, have high responsivity and allow simple signal processing. The photovoltaic detectors generate an electric current when infrared radiation is incident and have high responsivity and a fast response speed. HgCdTe or PbSnTe detectors are also included in the intrinsic type detectors. Controlling the composition of the ternary mixture can change the wavelength of peak responsivity of these detectors. In particular, the HgCdTe detectors are useful since they respond to wavelengths in the 3 to 5 μm and 7 to 13 μm ranges. Extrinsic Type Detectors are photoconductive detectors whose wavelength limits are determined by the level of impurities doped in high concentrations to the Ge or Si semiconductors. The biggest difference between intrinsic type detectors and extrinsic type detectors is the operating temperature. Extrinsic type detectors must be cooled down to the temperature of liquid helium.

Of the various types of commercial detectors, uncooled bolometers are used in the far infrared region of the spectrum (Meyer et al., 1996; Liddiard et al., 1996). Uncooled arrays are currently used in the SWIR region (Kozlowski et al., 1996) or in the Far Infrared Region. In the mid infrared region, commercial imagers are available only with cryogenic cooling. The three different types of cryogenically cooled mid infrared imagers include the micro-bolometers, InSb and HgCdTe. The biggest disadvantage with cryogenic cooling is that the lifetime of the coolers are in the order of 5000 to 10000 hrs. Long life cryogenic cooling based on the Joule Thompson effect is just becoming available (Hansen, 1996). However, a German group is using these coolers only with research infrared arrays. The second disadvantage with cryogenically cooled infrared imagers is that they do not tolerate very high operating temperatures such as those present on the factory floor. Finally, all these infrared imagers cost more than $ 10,000. This makes it almost impossible to use for routine on-line applications.

One method of eliminating the high cost of infrared arrays is to utilize a scanner in conjunction with single element sensors. Scanners are typically used in hyperspectral imaging applications, primary for observing earth based (Porter and Enmark, 1987; Green et al., 1990; Lehmann et al., 1995). The primary advantage of using scanners is that the technology is mature and cost effective. However, multi-spectral infrared imagers using single element sensors with scanners are not yet commercially available.

In summary, a range of techniques is currently being utilized for monitoring leaks from natural gas pipelines. A summary table highlighting the various techniques for natural gas leak detection is attached as Appendix-A. Any single technique has not yet become the industry standard due to the various limitations involved in the different techniques.

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Appendix-A: Comparison of Different Natural Gas Leak Detection Techniques

Technique	Feature	Advantages	Disadvantages
Acoustic sensors	Detects leaks based on acoustic emission	Portable Location identified Continuous monitor	High cost Prone to false alarms Not suitable for small leaks
Gas sampling	Flame Ionization detector used to detect natural gas	No false alarms Very sensitive Portable	Time consuming Expensive Labor intensive
Soil monitoring	Detects tracer chemicals added to gas pipe line	Very sensitive No false alarms Portable	Need chemicals and therefore expensive Time consuming
Flow monitoring	Monitor either pressure change or mass flow	Low cost Continuous monitor Well developed	Prone to false alarms Unable to pinpoint leaks
Dynamic modeling	Monitored flow parameters modeled	Portable Continuous monitor	Prone to false alarms Expensive
Lidar absorption	Absorption of a pulsed laser monitored in the infrared	Remote monitoring Sensitive Portable	Expensive sources Alignment difficult Short system life time
Diode laser absorption	Absorption of diode lasers monitored	Remote monitoring Portable Long range	Prone to false alarms Expensive sources Short system life time
Broad band absorption	Absorption of broad band lamps monitored	Portable Remote monitoring Long range	Prone to false alarms Short system life time
Evanescent sensing	Monitors changes in buried optical fiber	Long lengths can be monitored easily	Prone to false alarms Expensive system
Millimeter wave radar systems	Radar signature obtained above pipe lines	Remote monitoring Portable	Expensive
Backscatter imaging	Natural gas illuminated with CO2 laser	Remote monitoring Portable	Expensive
Thermal imaging	Passive monitoring of thermal gradients	No sources needed Portable Remote monitoring	Expensive detector Requires temperature difference
Multi-spectral imaging	Passive monitoring using multi-wavelength infrared imaging	No sources need Portable Remote monitoring Multiple platform choices	Expensive detectors Difficult data interpretation