Seeing and Hearing Methane Emissions from Buried Pipelines in the Midstream Sector

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Abstract

This Lamar University research project promotes adapting novel and innovative methane-detection technologies for solving challenges faced by the petroleum industry in the midstream arena through enhancing resiliency. Our research further promotes the public good by coordinating with the Texas Commission on Environmental Quality (TCEQ) in protecting Texas's public health and natural resources in providing affordable compliance. In 2003 the Texas Commission on Environmental Quality ordered studies to determine whether Optical Gas Imaging technology, via infrared cameras, could be used to better monitor fugitive emissions, or addressing the inadequacies of the EPA's Method 21. Natural gas leaks pose a clear risk of explosions, cause product loss, and the release of potent greenhouse gases. Persistent emissions from the natural gas infrastructure (e.g., well pads, compressors, and gas plants) jeopardize the role of natural gas as a clean energy. Acoustic sensors have long been used to detect water pipe leaks and above-ground methane leaks from natural gas compressor stations. This proposed project will further enable "hearing" through employing dual acoustic sensors for detecting these leaks and thereby home in on identifying the location of leaks from buried natural gas pipes. The acquired data will be processed to reveal the signature frequencies and the leak location by evaluating the signal delay between sensors. The addition of acoustic sensors will enhance identification of leaks; the full complement of detectors will let us "see" with a tunable diode laser absorption spectroscopy (TDLAS), and "probe" methane residue for our fluid-flow analysis, but further will leverage the ability to "hear" the provenance of gas leaks.

We will augment the optical detection of methane leaks with telltale acoustical signatures. The addition of these acoustic devices will enable line inspectors to "hear" the gas leaks from pipelines buried beneath various soils specific to Southeast Texas, such as Beaumont clay, river silt, and beach sand. Acoustic signatures will provide an additional means towards identifying the location of the leak. We will employ two types of listening devices that span from very low (4 to 500 Hz) to very high frequencies (20 to 40 kHz). In the future, data fusion systems from multiple sensors will afford us a mechanism to positively identify the leak species, leak location, and leak rate with the objective of finding and repairing remote pipeline ruptures. Towards this end, artificial intelligence tools such as the MATLAB neural network toolbox coupled with the predictive maintenance toolbox will be indispensable. The experimental data from this research with serve as a basis to validate future computational fluid-dynamics modelling of methane transport through various soil media. The project will be the foundation for seeking extramural funding to the federal agencies: DOE, USEPA, and USPHMA, as well as within Texas through the TCEQ. Further, we will certainly explore opportunities with the Pipeline Research Council International and other industrial entities.

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Glossary

Acoustic Signature: The unique frequency pattern emitted by a methane leak, as captured by dual acoustic sensors.

Fugitive Emission: Unintended and uncontrolled release of gases, such as methane, into the atmosphere.

Methanotroph: A type of bacteria that consumes methane as its primary source of carbon and energy.

Optical Gas Imaging (OGI): A technology that uses infrared cameras to visualize gases based on their absorption of IR radiation.

Tunable Diode Laser Absorption Spectroscopy (TDLAS): A laser-based technique for measuring gas concentrations through wavelength-specific absorption.

Computational Fluid Dynamics (CFD): A simulation method used to model the behavior of fluids (or gases) as they flow through various media.

Eulerian multiphase model: A CFD approach that treats each phase as a continuous medium with its own conservation equations.

Gidaspow granular viscosity model: A model that determines the effective viscosity of granular flows by accounting for particle interactions and collisions.

k-ε turbulence model: A CFD turbulence model that uses two equations, one for turbulent kinetic energy (k) and one for its dissipation rate (ε), to simulate turbulence and flow instabilities.

List of Acronyms

CMMS: Center for Midstream Management and Science
TCEQ: Texas Commission on Environmental Quality
OGI: Optical Gas Imaging
TDLAS: Tunable Diode Laser Absorption Spectroscopy
CFD: Computational Fluid Dynamics
PCR: Polymerase Chain Reaction
EPA: Environmental Protection Agency
DOE: Department of Energy
USEPA: United States Environmental Protection Agency
USPHMA: U.S. Pipeline and Hazardous Materials Safety Administration
PRCI: Pipeline Research Council International
LIT: Lamar Institute of Technology

1 Executive Summary

The Lamar University Center for Midstream Management and Science (CMMS) is establishing a dedicated facility in the Beaumont area for midstream research. This paper details our integrated approach for methane-leak detection, which combines optical and acoustic sensing with advanced data analytics and CFD modeling. Our experimental testbeds mimic realistic pipeline conditions, while high-resolution optical measurements capture granular surface emissions. Subsurface methane is measured with mass spectrometry to understand leak dynamics in varying soils. In parallel, we are developing a sophisticated mathematical framework for analyzing acoustic signatures obtained from dual sensors. This framework aims not only to localize leaks but also to characterize their severity and flow behavior, a significant advancement over traditional sniffer-based methods. These efforts are supported by strategic partnerships with local industry, academic institutions (including collaborations with the Lamar Institute of Technology and Infrared Cameras Inc.), and state agencies.

2 Introduction

Methane leaks from natural gas pipelines pose a serious risk to public health, safety, and the environment. In the midstream sector, undetected leaks can lead to explosions, product loss, and increased greenhouse gas emissions, issues that undermine the role of natural gas as a clean energy source. Traditional leak detection methods, such as methane sniffers based on EPA Method 21, have struggled with environmental variability, which causes methane to migrate unpredictably and emit from localized areas. In response, our research integrates advanced optical gas imaging with acoustic leak detection and data-driven modeling to provide a more comprehensive understanding of methane migration. This paper outlines our approach, experimental setup, and the development of an advanced mathematical framework for acoustic signature analysis, which we believe will enhance leak detection and characterization.

3 Content

3.1 Research Methodology and Experimental Design

Our detection strategy employs state-of-the-art infrared cameras to perform remote optical gas imaging, which is critical for visualizing methane emissions at specific points of atmospheric release. Complementing this, dual acoustic sensors are deployed, one set capturing low-frequency signals (4–500 Hz) and another set capturing high-frequency signals (20–40 kHz). These sensors are strategically placed on both the pipeline to record acoustic emissions associated with leaks. While other approaches have used dual sensors solely for localization, our method integrates these data streams into a robust mathematical framework that extracts signature frequencies and analyzes signal delays. This analysis not only detects leaks but also quantifies leak severity and flow characteristics.

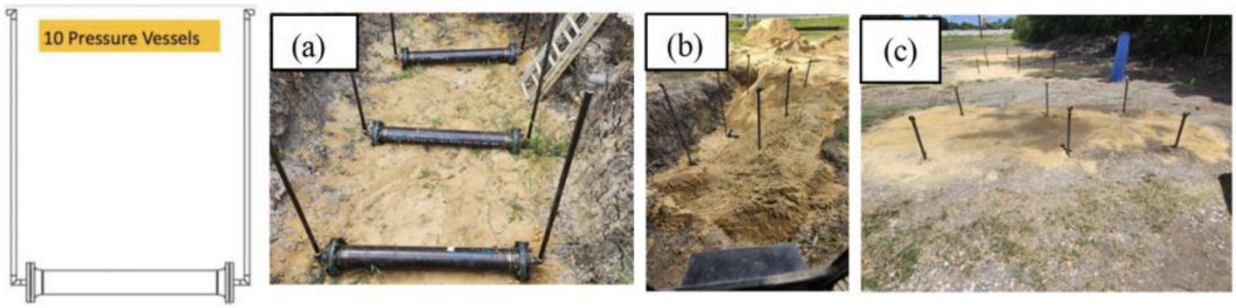

Fig. 1. At the Infrared Cameras Inc. site. (a) Three pressure vessels per trench for a given soil type; we have one spare. The pressure vessels are positioned so that the 1/8" holes are at 12 o'clock, 3 o'clock, and 6 o'clock. (b) In the process of burying the pressure vessels, two are visible. (c) The soil is fully packed down, with the 1" intake and outtake piping emerging from the soil in of the three trenches on ICI property as depicted in the photograph.

Experiments are conducted on a testbed located at the Infrared Cameras Inc. property, designed to simulate industrial pipeline conditions. The setup includes multiple trenches filled with distinct soil types, Beaumont clay, river silt, and beach sand, where pressure vessels with controlled leak points (1/8-inch apertures), are installed according to industry standards. Additionally, a methane capture grid consisting of 136 high-density plastic chambers fitted with highly sensitive methane sensors enables real-time monitoring of surface emissions. Environmental sensors distributed at various depths measure temperature and moisture, providing essential data for understanding how these factors influence methane migration.

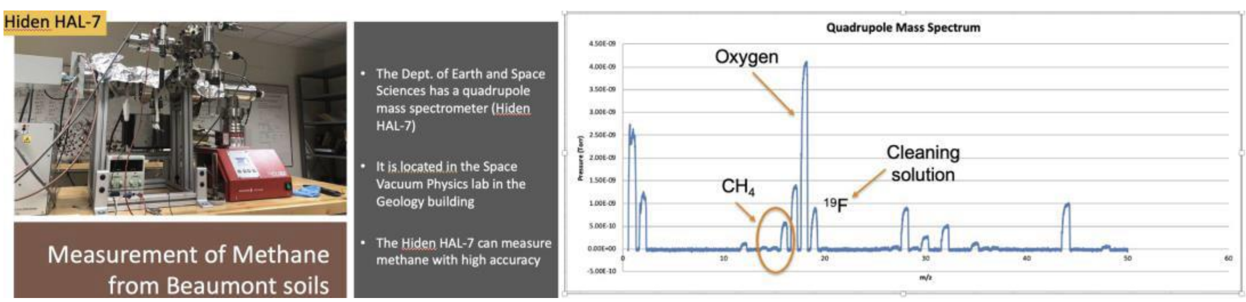

Fig 2. (a) The Hiden Hal-7 Mass Spectrometer operates under ultra-high vacuum to give precise measurements of gas content in soils. (b) Results from one measurement of Beaumont Clay (of the 27 samples) from the first set of trenches at Infrared Cameras Inc. as shown in the photograph in Fig. 1

A key innovation in our work is the integration of high-resolution optical measurements with subsurface methane data obtained from a quadrupole mass spectrometer. These dual data sets allow us to define accurate boundary conditions for advanced CFD models, which simulate methane transport through heterogeneous soil media. Incorporating dynamic environmental inputs, such as temperature and moisture profiles, further refines these models. In parallel, our advanced mathematical framework for acoustic signature analysis processes data from dual acoustic sensors using MATLAB's neural network toolbox and predictive maintenance algorithms. This framework is designed to extract detailed acoustic signatures, quantify leak flow rates, and assess the severity of leaks, providing a more nuanced analysis than traditional dual sensor approaches.

Complementing our sensor-based investigations, the experimental design also includes a focused methanotroph study to explore soil remediation strategies. In dedicated experimental rings, contaminated soils receive various amendments, such as compost, to enhance the growth and activity of methanotrophic bacteria. Periodic sampling combined with PCR-based microbial analysis quantifies changes in methanotroph populations, while real-time mass spectrometry monitors corresponding shifts in soil methane levels. This integrated approach aims to identify optimal treatment combinations that maximize methane oxidation, thereby contributing to a comprehensive strategy for mitigating methane leaks in the midstream sector.

3.2 Results, Discussion, and Implications

Preliminary testing has revealed that conventional methane sniffers are limited in their effectiveness. Environmental factors, such as soil heterogeneity and moisture, lead to unpredictable methane migration. As a result, broad-based sniffer approaches often fail to capture localized surface emissions, underscoring the need for more precise, targeted optical measurements.

High-resolution surface emission data obtained from our methane capture grid provides critical boundary conditions for CFD simulations. These detailed measurements enable us to map zones of active methane release with high spatial accuracy, which in turn improves the calibration and predictive capability of our models.

By continuously monitoring temperature and moisture at various soil depths, our experiments capture the dynamic influence of environmental factors on methane migration. Incorporating these data into CFD models has the potential to yield more accurate simulations of subsurface methane behavior, ultimately guiding more effective leak detection and remediation strategies.

Our innovative mathematical framework for acoustic signature analysis represents a significant advancement over traditional dual sensor methods. This framework not only enhances the localization of methane leaks but also characterizes their severity by analyzing signature frequencies and signal delays. Such detailed acoustic profiling allows for a better understanding of leak dynamics and flow rates, facilitating more targeted maintenance and repair efforts.

Preliminary analyses of methane-contaminated soils have revealed a significant deterioration in microbial activity. Preliminary morphological data indicate that methane exposure adversely affects the native soil microbiome, reducing both the diversity and functionality of microbial communities. This decline in microbial health not only hampers natural remediation processes but also underscores the urgency of developing targeted strategies, such as methanotroph-based remediation, to restore soil ecological balance and enhance methane oxidation.

Preliminary CFD Modeling Results

Computational Fluid Dynamics (CFD) modeling is a useful tool for understanding methane gas migration from underground pipelines. The simulation process begins with geometry creation, where the computational domain is divided into two main regions: the soil domain, representing underground conditions, and the atmosphere domain, where gas disperses upon surface release.

The buried pipeline is defined with a specific depth (4 feet), diameter (6 inches), and leakage apertures (1/8 inches). The operating pressure is set at 2-100 bar, with gas composed primarily of methane (83%), along with other hydrocarbons and inert gases.

The meshing process involves refining elements near critical areas such as the leak source and the soil-air interface. The element size varies, with finer resolution (6×10^{-3} m) at the inlet and coarser elements (5×10^{-2} m) in the outer soil and atmospheric regions. A mesh independence study determines the optimal balance between computational efficiency and solution accuracy.

The CFD model setup involves selecting appropriate physical models to simulate multiphase flow. The Eulerian multiphase model represents methane, soil particles, and air as separate phases. A k-ε turbulence model captures flow instabilities, while the Gidaspow granular viscosity model describes soil behavior. Boundary conditions include velocity inlets (ranging from 13.06 m/s (silty soil) to 188.88 m/s (gravelly soil)), pressure outlets (set to 0 bars), and no-slip walls for pipeline boundaries. Soil is assigned a density range of 1000–1600 kg/m³, with a particle size of 1 mm, either constant or varying through a population balance model.

Throughout the simulation, the time step size varied between $1\text{x}10^{-5}$ s to as high as 1 s. Generally, a smaller time step enhances accuracy but significantly increases computational time. Therefore, determining an optimal time step that balances accuracy and efficiency is crucial. The maximum number of iterations per time step was set to 100 for the entire project.

Methane is primarily spreading horizontally at the surface due to a sand cloud blocking its upward movement, increasing the risk of ignition near the ground. To effectively monitor and mitigate these risks, sensors should be strategically placed in areas where methane is most likely to accumulate. Deploying an array of sensors near the surface will help detect horizontal dispersion, ensuring comprehensive coverage of concentration changes. Additionally, placing sensors along the boundary of the sand cloud will allow monitoring of potential vertical escape points where methane might eventually rise.

High-risk areas near ignition sources, such as equipment or static discharge zones, should be closely monitored with sensors to provide early warnings. While surface-level detection is the priority, installing a few vertical sensors above the sand cloud can help track any delayed methane release. Establishing a distributed sensor network with redundancy in critical locations will improve reliability. Continuous data logging will help analyze concentration patterns over time, and fine-tuning sensor calibration along with an integrated alert system will further enhance safety measures.

Parameter	**Value**
Operating Pressure	2-100 bar (Specifically 50 bar)
Operating Temperature	12-32 ^{0}C
Pipeline Depth	4 feet
Orifice size	1/8 inches
Soil Type	Sand
Soil Volume fraction	0.63
Leakage Velocity	13.08 m/sec (Calculated)

Table.1: Pipeline conditions as provided by ICI Experimental site of underground pipeline and some calculated manually by excel sheet for simulation

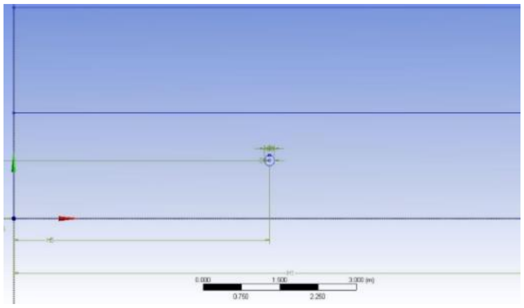

Figure 3 Geometry Dimension in Fluent Ansys

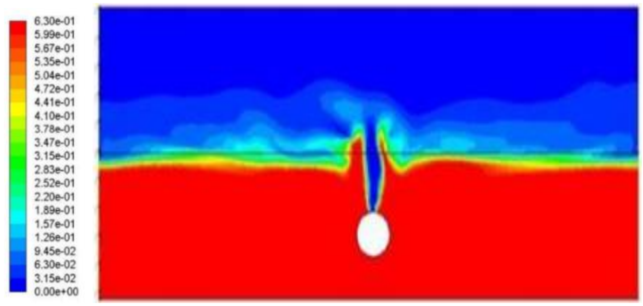

Figure 4 Sand Volume fraction after some time (4 sec)

4 Conclusions & Overall Recommendations

4.1 Summary of Key Findings

This study demonstrates that an integrated approach, combining optical gas imaging, advanced acoustic sensing, and high-resolution data fusion, can provide critical insights into methane leak detection and characterization. Key findings include:

- Conventional methane sniffers are limited by unpredictable environmental influences, resulting in missed localized emissions.
- High-resolution optical measurements and subsurface mass spectrometry can offer precise boundary conditions for CFD models.
- Dynamic environmental data (temperature and moisture) significantly enhance model predictions of methane migration.
- The development of a robust mathematical framework for acoustic signature analysis offers a dual advantage of improved leak localization and detailed characterization of leak severity.
- Preliminary analyses indicate a marked deterioration in microbial activity within methane-contaminated soils, highlighting the need for and potential effectiveness of methanotroph-based remediation strategies.

4.2 Recommendations for Industry and Future Research

Based upon our preliminary findings, we recommend:

- Adopting integrated optical and acoustic detection systems that utilize advanced data analytics for precise methane leak monitoring.
- Expanding field experiments to further refine CFD models and validate our mathematical framework under varying environmental conditions.

- Pursuing collaborative partnerships with local industry, academic institutions (including Lamar Institute of Technology), and state agencies to advance research and secure funding for broader implementation.
- Continuing to develop training and certification programs in collaboration with technical programs in industrial mechanics, instrumentation, and process operating technology to support the deployment and maintenance of these advanced detection systems.
- Conducting further studies on remediation techniques, with a particular focus on methanotroph-based approaches, to determine their efficacy in restoring microbial activity and reducing methane concentrations in contaminated soils.

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