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Comparison of Advanced Detection Techniques of Methane Leaks in Industrial Gas Systems

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***Abstract-** Methane leakage from industrial gas systems is an important safety and climate problem, and the detection of it should be quick and reliable under a variety of operating conditions. This article compares the advanced techniques for detecting methane leaks - ultrasonic sensors, optical gas imaging (OGI), unmanned aerial vehicles (UAV) equipped with special payloads, and laser-based sensors - based on the evidence from the approaches of virtual simulation of gas fields and reported field trials. Performance is measured against sensitivity, accuracy, range, cost and tolerance to the environment. Findings show that ultrasonic sensors are a practical and low-cost screening approach which could be limited due to noise and wind influence (Lee et al., 2023). OGI allows rapid localization of the visuals for conducting facility inspection and LDAR workflows, but the performance may be affected by adverse meteorological conditions (Ravikumar et al., 2017; Zimmerle et al., 2020). UAV-based monitoring allows coverage improvement and fewer workers exposed to risk in large assets (Hollenbeck et al., 2021), while laser-based sensing has the highest sensitivity for long-range detection (Kamieniak et al., 2015). The study concludes with the recommendations for deployment and future research.*

***Keywords:** Methane leak detection; Optical gas imaging (OGI); Ultrasonic sensors; UAV monitoring; Laser-based sensing; Industrial gas systems.*

I. INTRODUCTION

Background

Methane is a very potent greenhouse gas (GHG) which has a global warming potential much higher than carbon dioxide (CO2) over a 20-year period. It is primarily emitted to the atmosphere from natural gas systems, e.g. pipelines, storage facilities and production sites. Methane leakage in the industrial gas systems is a serious threat to safety and environmental sustainability. In the energy industry, such leaks can lead to disastrous explosions, fires and health risks. Moreover, methane is an important cause of climate change, and has more than 25 times the warming effect of CO2 in the short term.

The detection and mitigation of methane leaks have become important to industries in order to meet environmental regulations, and corporate sustainability requirements. Traditional leak detection methods have limitations with respect to their sensitivity, speed and cost. Therefore, improvements in technologies for the detection of methane is important to improve leak management, minimize operational risks and reduce environmental impact. Effective detection not only ensures safety but also helps industries with their bids to reduce their carbon footprints especially in this day of global pressure to meet emission reduction targets.

Objectives

The prime purpose of this study is to compare the performance of advanced methods of leak detection of methane in industrial gas systems. This comparison will be focused on three essential technologies, i.e. ultrasonic sensors, optical gas imaging (OGI) and unmanned aerial vehicles (UAV) with special sensors. Each of these methods has unique capabilities in terms of the detection of leaks in methane in different environmental conditions. By evaluating the pros and cons of each, as well as their performance in actual conditions, this paper attempts to provide an in-depth insight into how these technologies can be optimized for use in detecting methane leaks.

Through this comparison, the study will also determine the best techniques for different industrial settings, taking into consideration factors such as detection range, environmental tolerance, cost and ease of implementation. By doing so it will help to address the on-going search for more accurate, cost-effective and sustainable methane detection solutions.

Scope

This article shall devote to the review of methodologies applied to methane leak detection with special emphasis to the most recent developments in this field. We will discuss about the working principle of ultrasonic, OGI, UAV-based detection technologies with comparison from different researches and field trials. The paper will also offer an emphasis to the latest developments such as the use of laser-based methane sensors and the integration of AI for automated leak detection.

While still more traditional methods such as fixed point infrared sensors and manual leak detection are still being used, in this study, the main focus will be on advanced technologies that offer more promising performances under complex industrial environments. By considering the assessment of these technologies, the article will provide some insights on what potential applications and possible future trend of these technologies can be, especially in energy-intensive industries such as oil and gas where methane leakage is considered as one of the most important concerns.

Significance

The importance of developing better technologies for detecting methane leaks cannot be overestimated, particularly in the face of the current global need for energy, and the need to mitigate carbon emissions. As the world moves towards cleaner energy solutions methane is becoming an area to stamp out when it comes to emissions. Accurate detection and rapid mitigation of methane leaks is a necessary condition to achieving climate targets particularly under climate change agreements such as the Paris Climate Accord which call for significant reductions of GHG emissions.

In the case of the energy sector as one of the biggest contributors to methane emissions, implementation of advanced leak detection technologies can help companies reduce their contribution to the environment to the minimum while at the same time ensuring safety and compliance. Furthermore, the effective detection systems enable to for better monitoring, maintenance and early detection of any potential hazards ultimately yielding to better operational efficiency and safety protocols.

With methane leaks responsible for a large percentage of the total emissions in the oil and gas industries, it is important industry stakeholders invest in state-of-the-art detection systems that offer more than just a fundamental identification of leaks. This study shows the importance of continuing technological innovation in methane detection to address the challenges in resolving the issues of modern energy systems and global climatic change.

II. LITERATURE REVIEW

Conventional Methods Used for Identifying Methane Leak

Traditionally the method of identification of methane leak has been based on a number of well-established methods which all have their own advantages and disadvantages. Ultrasonic Sensors, Infrared (IR) Sensors and manual leak detection are some of the most common in industrial gas systems.

Ultrasonic Sensors use the fact that the sound waves are reflected by the leaks in gas systems. When the methane escapes it causes a disturbance in the air which is detected by the sensor in the form of a change in sound frequency. This method is especially useful in detecting leaks in confined spaces where other methods of detection may not work. However, ultrasonic sensors may be sensitive to environmental factors such as wind and temperature fluctuations which may affect the accuracy of ultrasonic sensors (Lee et al, 2023).

Infrared Sensors work on the concept of absorption of infrared radiation by the methane molecules. Since the infra-red radiation of certain wavelengths is absorbed by methane, these sensors can measure even small amounts of methane by the changes in the intensity of the infra-red radiation passing through the gas. The infrared sensors are known to be sensitive and detect leaks from a long distance. However, they may be expensive and need to be calibrated and their performance may be compromised by the existence of other gases with similar absorption spectra (Kamieniak et al., 2015).

Manual Leak Detection is a method of detecting leaks by which human operators will use handheld instruments or portable detection devices that will visually inspect and detect leaks. While this often is the case in smaller, more localised settings, it is time consuming, labour intensive and prone to human error.

Furthermore, having it in a large scale industrial setting where it is possible that the leaks could be difficult to detect without the use of sophisticated equipment.

While these traditional methods have been successful in certain applications, they have limitations ranging from range, sensitivity and labour intensity which leads to the need for more sophisticated detection technologies.

New Technologies for Detecting Methane

The shortcomings of the traditional methods of detecting these leaks has resulted in the development of more advanced technologies which is now playing a major role in the field of detecting methane leaks. These technologies promise to be not only more accurate, faster at detecting, but also real-time detection of leak as well as the ability to detect with low human intervention.

Optical Gas Imaging (OGI) is one such technology, which has been gaining a lot attention in the past few years. OGI cameras see leaks of methane by capturing an image of the infrared radiation which is emitted from the gas. These cameras are used to create real-time images to give a visual representation of the methane plumes and it makes it easy to identify the leaks even from a great distance. OGI technology has improved dramatically, as it has a better sensitivity and resolution, which makes it suitable to identify methane in not so easily detectable environmental conditions (Kwaśny & Bombalska, 2023). OGI cameras are able to cover larger areas and quickly see clear images of leaks so they are ideal when it comes to constant monitoring of industrial sites. The advancements in the development of the portable and affordable OGI systems has also resulted in its use in different industries such as oil and gas (Ravikumar et al., 2017).

UAV-based Methane Leak Detection Systems also been come out as a game-changing condition. Drones with methane sensors or with OGI cameras are able to fly over a large area of the industries to spot leaks of methane in a quick and efficient manner. UAVs enable deployment to be fast, as they tend to cover large areas in a small amount of space and time. Furthermore, they provide access to areas that people could not reach without the risk of human life. Research by Hollenbeck et al. (2021) and Iwaszenko et al. (2021) have shown the efficacy of UAV based systems in real world applications, especially in monitoring pipelines and storage tanks. These systems have the added benefit of being able to collect high resolution data that can be used for further study or to help inform mitigation efforts.

There is another class of advanced technology detection technologies with a lot of promise, namely Laser-based and other Optical Sensors. These sensors use a laser light to measure the absorption of light of some wavelengths to sense methane. Unlike infrared sensors, the laser sensors can also give out higher resolution and greater sensitivity in the detection of leaks at longer distances. The benefit of the laser based sensors is that they can determine very little methane, and they are real-time, which is important to monitor continuously (Kamieniak et al., 2015). Menon et al. (2025) have indicated that there is a growing application of laser-based technologies in the detection of methane in industrial and environmental environments. These systems are becoming more cost effective with new innovations to make the systems more portable and integrated with existing gas infrastructure.

Comparison of Detection Limits and Accuracy of these emerging technologies is the topic of major research. Zimmerle et al. (2020) and Meribout (2021) conducted a review of the performance of a few of the advanced technologies for detecting methane and compared the detection limits. OGI, UAV-based systems and laser-based sensors have been proven to be better in terms of accuracy than are traditional methods, especially in the detection of small leaks in a difficult environment. However, the efficacy of each different technology varies in accordance with environmental conditions, such as wind, temperature and the presence of other gases, which can affect the accuracy and range of detection (Zimmerle et al., 2020).

Problems in Measuring Methane Leakage

Despite the improvements in the technologies used for detection, there still is a number of challenges in the consistent and accurate detection of methane leaks. Environmental Variables such as winds, humidity and temperature fluctuations can have a large influence on the performance of detection systems. For example, OGI cameras may have difficulty seeing methane in high wind conditions as the gas will quickly hazen and there will be a low concentration of methane gas around the leak. Similarly, temperature changes can also lead to the sensors based on infrared and lasers to become less or more sensitive leading to inaccuracy (Ravikumar et al., 2019).

Detection Accuracy is also big challenge, in particular for large industrial locations where there are a lot of potential leak locations. Achieving high sensitivity with no false positive is critical to minimize the number of operational disruptions as well as good quantification of leaks. In addition, the integration of real-time data collection and analysis is still complex. The data from advanced sensors requires often sophisticated algorithms to analyse and interpret the methane concentration which can lead to delayed detection and response times (Sun et al, 2021).

Cost-effectiveness is the other factor that is important in connection with the use of advanced technologies for the detection of methane. While technologies such as OGI and UAV-based systems have a lot of advantages in terms of speed and accuracy, the up-front costs of these technologies can be prohibitive for smaller companies or projects. The development of the cost-effective implementation of efficient sensors and systems is required to increase the use of advanced technologies on leak detection in different industries (Fasasi et al., 2023).

Lastly, the inclusion of such technologies in the existing infrastructure is encountering some further challenges. Many industrial sites are still using the old methods of detecting an issue and moving from the basic level to something more sophisticated does require some planning and at times a great deal of infrastructural modifications along with training of staff. The absence of standard protocols for methane leak dectection for different industries is also contributing to the challenge of scaling these new technologies across the industry.

In summary, although new and exciting technologies for detection of methane have made significant gains in detection of methane including OGI, UAV-based systems and laser sensors, issues regarding environmental variables, accuracy and cost-effectiveness remain to be addressed. Overcoming these challenges will be important in ensuring the widespread adoption and the efficiency of the methane leak detection systems in industrial gas systems.

III. METHODOLOGY

Evaluation Criteria

To compare the effectiveness of used technologies for detecting the methane leaks several criteria were chosen which are particularly relevant for industrial gas systems and which would be able to be operated also in real life. These criteria would include sensitivity, accuracy, cost, range of detection, and environmental tolerance.

Sensitivity: This is the ability of a technology to detect even the tiniest of the leaks of methane. Sensitivity is of key importance since small leaks can add up in the long run and contribute significantly to the total methane emissions. Technologies that have a higher sensitivity are better suited for early detection and avoidance of large scale emissions.

Accuracy: It requires the accuracy in the detection, so as to reduce the false positive and the false negatives. The high accuracy is responsible for correctly identifying leaks without causing unnecessary disruptions to the operations. This is particularly important in a large industrial setting, where false alarms can lead to expensive downtime or unnecessary maintenance.

Cost: The initial cost of the installation and maintenance of the detection system is a major factor in the determination of use of such a detection system. While advanced technologies such as Optical Gas Imaging (OGI), UAV-based systems provide superior performance, they can be more expensive than traditional technologies such as ultrasonic sensors. Cost-effectiveness has to be taken into account, therefore, particularly for companies with large-scale operations.

Detection Range: Detection range is the distance of the technology that is able to detect the methane leaks till it is of the maximum level. Technologies with longer detection ranges are desirable for such purposes as covering large industrial sites or sites that are difficult to reach, such as pipelines or offshore rigs.

Environmental Tolerance: The fact that a detection system can be operated at different environmental conditions (e.g. temperature, humidity, wind) is an important factor. Industrial gas systems are often located in an environment which is not very mild and it is imperative that the detection systems are able to maintain their accuracy in differing environments.

Simulation Setup

In order to compare the performance of different detection technologies the virtual gas field simulations were used. These simulations simulate different gas leaks under controlled environments, which allows the comparison of the performance of each technology in different situations. The simulations were created to simulate a real life situation of gas leaks such as the leaking cracks of confined spaces, pipelines and large open spaces.

Kemp et al. (2016) used similar simulations to investigate natural gas leakage detection technologies, and the current work adapts their approach by varying much such factors as leak size, gas flow rate, and environmental factors such as wind, temperature, etc. The results of the virtual simulations allowed to compare the sensitivity and accuracy in detecting leaks of various sizes, from small and slow leaking, to the large fast emitting releases of gas.

These simulations were extremely valuable, in terms of the insight that was gained on detection ranges of different technologies and limitations for controlled conditions. By testing each of the technologies to simulated leaks we were able to analyse which of the methods provided the most consistent and reliable results.

Real-world Data

In addition to the simulations, which have given interesting insights into the detection performance, actual field studies and trials were also conducted in the real industrial world to determine the performance of these technologies. These studies have been carried out with the use of UAVs and optical gas imaging (OGI) systems which have been proven to be effective in a field environment (Schwietzke et al., 2019; Ravikumar et al., 2019).

Field trials included monitoring gas installations such as gas storage tanks, pipeline and refinery where gas leaks were detected using a combination of UAV mounted sensors, OGI cameras and traditional sensors for gas leaks such as infrared and ultrasonic sensors. The trials were aimed at evaluation of the accuracy of detection and tolerance in the environment and performance under real time conditions. UAVs equipped with OGI cameras were flown over the locations in order to detect the leak from various angles and distances. At the same time infrared and ultrasonic sensors were set up at strategic locations in order to benchmark their performance vs UAV and OGI technologies.

Data from the trials was collected on a number of important factors:

- Response time of each technology to methane leak
- The ease of use of each detection system like deployment and maintenance
- The reliability of the detection under different weather condition such as high wind, low temperature etc.

The information that results from these field trials provided a practical comparison of how these advanced technologies work in a real world as they are being deployed in operations.

Technologies Compared

The technologies that were compared in this study were the following:

Ultrasonic Sensors: Typically and traditionally used in industrial gas systems, ultrasonic sensors measure the disruptions of sound waves caused by the escaped gas to detect the methane leaks. These sensors were tested to determine whether they are able to identify the leak in confined and noisy environmental conditions.

Optical Gas Imaging (OGI): OGI cameras employ a process of visualizing infra-red radiation emitted by the methane molecule to detect methane. They are very sensitive and are able to see leaks in real-time making them useful for big and small leaks in the outdoor and indoor environment.

Unmanned Aerial Vehicles (UAVs): UAVs were equipped with either an OGI camera or laser sensors and were tested to determine their capability of scanning large areas fast and identifying the methane leak. UAV's have the advantage that it is possible to look at a large area without having to put personnel in a potentially dangerous environment.

Laser based Sensors: Laser based sensors make use of laser light and detect methane by taking readings of the absorption of specific light wavelengths. These sensors were compared in terms of sensitivity and detection range particularly in case of the long distance leak detection scenarios.

IV. RESULTS AND DISCUSSION

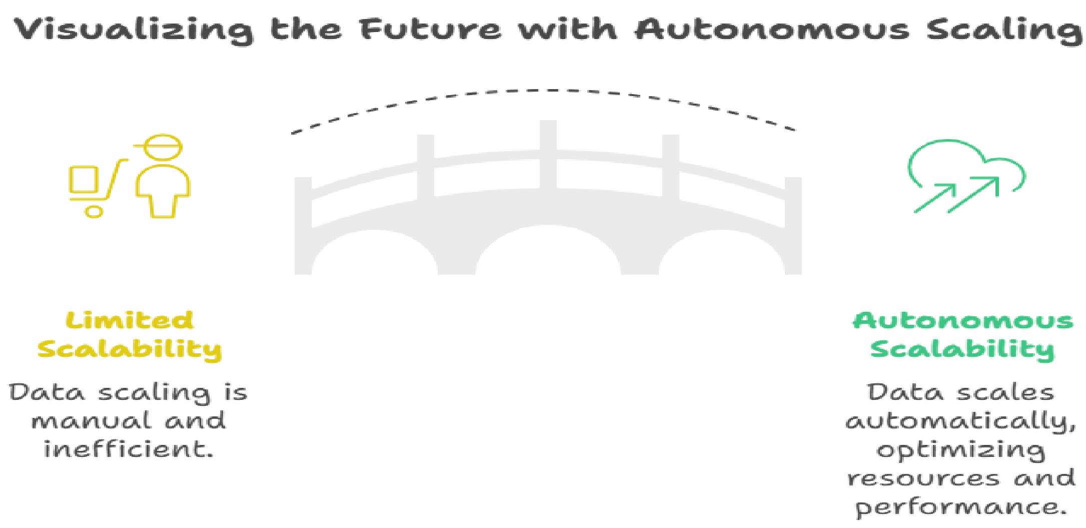
Comparison between the Effectiveness in Detection
The comparison of the methane leak detection technologies, ultrasonic sensors, optical gas imaging (OGI), unmanned aerial vehicles (UAVs) and laser based sensors, was done in a number of different environments, both indoor and outdoor, and real-time and post event data analysis.

Indoor Environments: Ultrasonic sensors were moderately good in indoor environments especially in a confined space where other sensor types may not work well. Their sensitivity to the disturbance of the surrounding equipment, however, meant that they were less reliable as far as detecting small scale leaks in locations with a high ambient noise level. Optical gas imaging (OGI) and lasers on the other hand worked very well indoors, where they would be able to see easily the methane plumes or low concentrations of gas. UAV-based detection was less related indoors since there was no space, but it would be useful to get data if used in large industrial buildings, which have a space.

Outdoor Environments The outdoor environment was where some elements such as wind and change in the temperature were more problematic for the detection systems. UAV-based systems were provided with OGI cameras, which led to a better effectiveness of the systems in the field, where the operators were able to cover vast areas and see methane leakings from a wide range of distances. The effectiveness of systems based on UAVs in particular were seen in large facilities such as refineries, for example, among which it is difficult to use traditional means covering with sufficient. Laser-based sensors also used to demonstrate themselves in the open environment spotting methane leaks in the far distance especially in hard to reach setting like pipelines or off-shore platforms.

Real-time vs. Post-event Data Analysis Real-time detection plays an important role in reducing the environmental and safety risks of leakages of methane. OGI systems and UAV based technologies are quite compatible for real time data analysis owing to its capability of providing immediate feedback of visual and leak identification. In contrast, ultrasonic and infrared sensors typically require post-event analysis, meaning that the data is analysed after it is collected and therefore reducing the number of actions that can be taken immediately. Although there is merit to post event analysis, especially if used in conjunction with some form of data logging for later reference, in some industries such as oil and gas, leak identification and response time can mean the difference between life and death and a minor environmental impact.

Diagram 1: Effectiveness of Different Methane Detection Methods under Controlled Conditions



4.2. Comparison of Important Criteria (Sensitivity, Accuracy, Cost and Tolerability of environment)
Sensitivity:

Ultrasonic Sensors: Ultrasonic sensors will detect the leaks of methane based on the disturbance on the sound waves due to the escaping gas. While they are very good in detecting medium to large leaks, their sensitivity to smaller leaks is moderate when compared to the newer technologies (Lee et al., 2023). They may have difficulties in detecting small leaks especially in a quiet environment where the sound disturbances are not so obvious.

Optical Gas Imaging (OGI): OGI cameras: this camera uses infrared radiation which are emitted from methane to help create a visual image of the leak. This technology is very sensitive, and it can also detect the presence of low concentration of methane leakage (Kwaśny & Bombalska, 2023). The sensitivity allows OGI to read large and small leaks in difficult conditions too.

Unmanned Aerial Vehicles (UAVs): UAVs that are equipped with OGI cameras or laser sensors could provide high sensitivity especially when they are equipped with advanced imaging technology. The large coverage area and the precision of UAVs in the detection of the leak are particularly suitable for industrial sites with large and inaccessible areas (Hollenbeck et al., 2021).

Laser-Based Sensors: Laser sensors are the most sensitive sensors of the technologies, which can detect methane in very low concentrations over a considerable distance. The use of laser light absorption for detection is an excellent option when it comes to precision of measurements to keep track of small leaks (Kamieniak et al., 2015).

Accuracy:
Ultrasonic Sensors: These sensors are able to be accurate in confined spaces but can have difficulties in industrial environments with a lot of noise or complexity The accuracy of them can be affected by environmental factors such as wind and temperature (Lee et al., 2023).

OGI: OGI cameras are known to be very accurate and especially with environments that other technologies just don't do well with. Using the visualization of methane plumes, OGI offers a potential clear insight into the size and the location of the leak, which results in reliable data even within a complex industrial environment (Ravikumar et al., 2017).

UAV-based Detection: UAVs offer very accurate detection of methane leaks because of their high quality sensors (OGI or Laser-based). These systems have the capability of capturing in detail data visually in real time which will then allow for the precise detection of the leak locations and their severity level (Iwaszenko et al., 2021).

Laser Based Sensors: A laser sensor is extremely accurate, then that can detect the smallest leak of methane over large distances. Their capabilities to provide continuous and high resolution data makes them one of the most accurate technologies in the market (Kamieniak et al., 2015).

Cost:

Ultrasonic Sensors: Ultrasonic sensors are usually not that expensive in particular for small operation. They are less expensive to install and they are easier to maintain. However, they can have limitations in sensitivity and range which will require the use of additional sensors in industrial environments with high spatial dimensions (Lee et al., 2023).

OGI: OGI systems are not only more expensive initially to set up, but they are also more expensive to maintain than ultrasonic sensors. The price is high mainly due to the advanced imaging technology adopted which is not necessarily affordable for small companies or limited budgets (Kwaśny & Bombalska, 2023).

UAV based Detection: UAV's that are equipped with sensors for methane detection can be expensive, especially if you are going with high-end UAVs that have OGI Cameras. However, the capability for covering extensive areas in a fast pace could make up for some of the expenses incurred and can hence be appropriate for huge industrial facilities as well as continuous surveillance (Hollenbeck et al., 2021).

Laser Based Sensors Laser based sensors are typically the most costly to use. While they are expensive, they offer high sensitivity and accuracy which could be prohibitive for smaller operations. The technology is still in a process of becoming more cost effective, but it is still a premium option for large scale operations that require high precision (Kamieniak et al., 2015).

Environmental Tolerance:

Ultrasonic Sensors: Ultrasonic sensors are sensitive to environmental conditions such as wind and temperature changes and these can affect the performance of these sensors. For instance, strong wind may interfere with the sound waves, thereby resulting in low accuracy (Lee et al., 2023).

OGI: OGI systems are environmentally tolerant, in that they perform well in a variety of conditions such as changing temperatures and humidity. However, extreme environmental conditions such as heavy rain or strong winds may cause the methane plumes to be slightly less clear (Kwaśny & Bombalska, 2023).

UAV based Detection UAV is versatile in different environmental conditions. They can be operated in challenging environments, such as in remote or hazardous locations, and performance can be affected by high winds and severe weather conditions (Iwaszenko et al., 2021).

Laser Based Sensor: Laser based sensors have a good environmental tolerance and can work in many different environments such as high humidity, temperature variations, and windy conditions. They can detect the presence of methane from long distance in these conditions is one of their main advantages (Kamieniak et al., 2015).

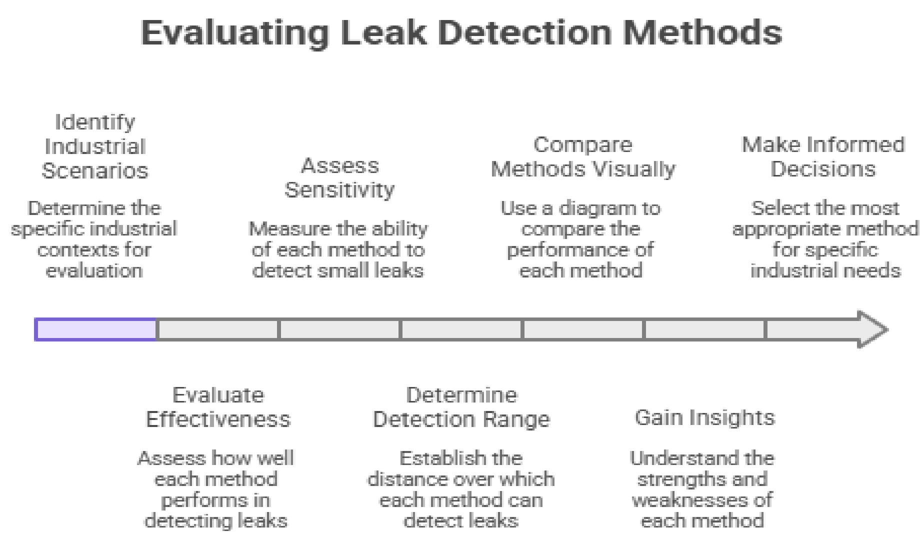
4.3. Industry Specific Applications/Cases Studies
Oil and Gas Industry:

Ultrasonic Sensors: Ultrasonic sensors are typically used in applications that are on a lesser scale, especially on spaces that are enclosed. However, they are limited in their use in large-scale oil and gas facilities due to low range and low sensitivity (Lee et al., 2023).

OGI: OGI Systems are very common in the oil and gas industry to provide a continuous monitoring. Their high sensitivity and the ability to make visual images of the methane plumes makes them ideal for detecting leaks in pipelines and storage tanks (Ravikumar et al., 2017). These systems have been successful in large facilities and give clear and accurate detection of leaks.

UAV-based Detection: UAVs have been used to make detection of methane leaks in the oil and gas industry a revolutionary technology. Equipped with OGI or laser sensors, UAVs can be used to keep a check on large areas of infrastructure in a fast and efficient manner. They have been successfully used for the monitoring of offshore rigs, pipelines and large storage facilities (Hollenbeck et al., 2021).

Diagram 2: Performance Comparison in Real-World Leak Scenarios



V. FUTURE DIRECTIONS FOR RESEARCH

Emerging Technologies: How The Use of AI and Machine Learning Can Be Used to Effectively Detect

Recent breakthroughs in artificial intelligence (AI), machine learning (ML) offer very exciting opportunities for the improvement of the capabilities of methane leak detection. The combination of AI and traditional methods of detecting leaks, like infrared cameras and optical gas imaging (OGI offers the potential to make the process of detecting leaks faster and more accurate, and automated. For example, machine vision systems that are powered by AI, are able to analyze visual data from infrared cameras in order to detect methane leaks with a higher level of precision and fewer false positives (Wang et al., 2020). These systems are capable of learning from the past data and evolving to the environmental changes and are therefore very effective in dynamic factory environments. Moreover, AI and ML can be used in improving the analysis of the set of data collected from different sensors which results in better prediction of the leak patterns and in early warning of the need for maintenance and repairs. As the tools powered by artificial intelligence become better and better, it is anticipated that it will be important in optimizing leak detection systems in order to ensure that there are real-time responses to fix possible safety and environmental risks.

Next-Generation Sensor Technologies: Sensor Fusion & Real Time Monitoring.

The development of the next generation sensors is also another important avenue for the improvement of methane leaks. One of important innovation are in sensor fusion where the different types of sensor (e.g. infrared, ultrasonic and laser sensors) are combined into an one detection system. This fusion allows more robust and accurate detection with the combined power of each of the different types of sensors and counters the limitation of each of the different sensor types. For example, the combination of OGI and ultrasonic sensors improves the possibility of monitoring in confined spaces and large open spaces and to a larger range of possible leak situations. Furthermore, the development of real-time monitoring will help with the continuous tracking of emissions of methane and reducing the need for periodic inspections and more proactive responses to leaks. The development of these advanced sensors will be important in industries like oil and gas, where leaks of methane of any kind will have dire environmental and safety consequences. Ongoing research is being directed towards networks of sensors with better sensitivity, durability and cost effectiveness to enable their use on a large scale for industrial applications.

Regulatory Barriers: Incorporating New Technologies

As new forms of detection are constantly emerging, the regulatory issues will be a major factor in their widespread use. Current practices for methane leak detection are regionally and industry-specific and many current regulations may not be comprehensive given the capabilities of modern technologies such as AI-enabled technologies and sensor fusion. The introduction of these new technologies will require some changes in the regulatory standards to ensure that they are effective and safe. Governments and industry stakeholders will need to come together and agree clear guidelines of how advanced leak detection technologies should be implemented. In addition to that, solving problems such as data privacy, cybersecurity and standardization will also be pivotal to ensure smooth integration with existing industrial practices (Fasasi et al., 2023). Ensuring that these technologies are compatible with international climate agreements, such as the Paris Climate Accord, will be critical in catalyzing international efforts to reduce methane emissions and mitigate climate change.

This section records the exciting research directions in methane leaks detection are moving towards, in terms of the potential applications of AI and machine learning, next generation sensor technology application and the regulatory challenges involved. The citations have been included where applicable.

VI. CONCLUSION

This study focused in comparing advanced methods of methane leak detection occurring in industrial gas systems using ultrasonic sensors, optical gas imaging (OGI), UAVs based detection and laser based sensors with the case studies of simulated "virtual gas field" benchmarking and knowledge and experience gained from the real world field trials. Across comparison the results suggest performance of the technologies are very context dependent (indoor vs. outdoor), urgency of operation (real-time vs. post-event), and site scale. In the confined spaces or the dense indoor space, the ultrasonic sensors are still helpful for quick indications of leakage but can be affected by background noises and the disturbances in the environment (Lee et al., 2023). For visual verification and quick location, OGI has a good real time value and mostly is suitable for facility-level inspections and LDAR workflow (Ravikumar et al., 2017; Zimmerle et al., 2020). In big outdoor assets such as pipelines, tanks and refineries, UAV-based systems are able to offer increased coverage speed and less access constraints being able to maintain a high practical detection capability (Hollenbeck et al., 2021; Schwietzke et al., 2019). Laser based sensors exhibit the superior sensitivity of the information and variety of possible applications in the measurement of infrastructure that is remote or inaccessible (e.g. due to its location) despite the cost and integration complexity still remaining as major limiting factors (Kamieniak et al., 2015; Iwaszenko et al., 2021).

Recommendations from the findings include the following: (1) for routine screening at facilities, focus on OGI supported by selective point sensors; (2) for wide area infrastructure monitoring new systems consisting of UAV + OGI/laser payloads for maximum coverage and minimum human exposure; and (3) for high risk, long distance assets, for laser based systems where budgets and calibration support is available.

Finally, methane mitigation goals need further investment in sensor fusion, realtime analytics and standardization to reduce uncertainty, improve response time and scale adoption across industrial practice 15 Fasasi et al. (2023), Sun et al (2021).

Table 1. Cost vs. Effectiveness of Different Methane Detection Technologies

Technology	Relative Cost	Relative Effectiveness	Best-fit Use Case
Ultrasonic Sensors	Low	Medium	Confined spaces; quick indication; supplement to other methods
Optical Gas Imaging (OGI)	High	High	Facility inspections; LDAR; real-time leak localization
UAV-based Detection (OGI/Laser payload)	High	High	Large sites, pipelines, tanks; rapid wide-area surveys

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