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CHEMICAL ENGINEERING TRANSACTIONS

VOL. 111, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Valerio Cozzani, Bruno Fabiano, Genserik Reniers

ISBN 979-12-81206-11-3; **ISSN** 2283-9216

DOI: 10.3303/CET24111013

The Use of Aerial Platforms for Identification of Loss of Containment

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Containment leaks in process plants pose a substantial risk, leading to potential fires, explosions, and toxic releases. Given the complexity of spill detection, monitoring is essential to promptly identify LOCs and minimize consequences. For in-depth analysis, it is important to constantly monitor large areas over time to gain a global view and identify any changes. At the same time, immediate inspection provides detailed data in real-time, allowing you to respond quickly in critical situations and it is particularly useful for analysing specific details. The utilization of aerial platforms, such as unmanned aerial vehicles (UAVs or drones), can be adopted for instant inspections, significantly improving their effectiveness. Initially employed for monitoring civil structures, drones have found applications in the process industry due to their flexibility, versatility, and precision. Equipped with carefully chosen sensors, drones can provide detailed information by approaching dispersed gases, enabling accurate calculations of quantities. Additionally, drones equipped with cameras offer the capability to visualize released gases and detect small fires from a safe distance, allowing for detailed observation without direct exposure to potential dangers.

This research represents a review of the state of the art with a specific focus on a gas, hydrogen, with significant potential to reduce environmental pollution and fossil fuel dependence. The wide flammability range and the low ignition heat of hydrogen pose risks of forming flammable mixtures with air during leaks, leading to spontaneous ignition. While existing studies have explored leak detection methodologies through mathematical models and laboratory-scale simulations, there is a gap in addressing real-scale hydrogen leak detection. The research proposes a meticulously designed monitoring system to safely identify hydrogen leaks, crucial in preventing potential jet fire phenomena when mixed with the surrounding air.

1. Introduction

"Loss of containment" (LOC) or "containment leaks" refers to the uncontrolled release of substances from a system or container with the potential risk of serious incidents such as fires, explosions, or toxic releases. Accidents caused by leaks of containment represent one of the most significant and serious categories of process accidents. These incidents can vary greatly in scale, from the release of non-hazardous materials to catastrophic events involving the release of hazardous chemicals and/or associated energy (Dharmavaram and Klein, 2010). They can be caused by various reasons within industrial plants. Some of the main causes include malfunctions of mechanical elements, failures or errors in control systems and/or plants, equipment design errors, ageing or degradation of materials used in the plant, human errors, extreme natural events (Rodriguez et al., 2023), and inadequate maintenance. The degree of danger depends on the materials involved, the operating conditions, and the effectiveness of the safety measures. Containment leaks pose significant risks to human health due to the release of toxic or harmful substances. Likewise, environmental risks arise as the substances released have the potential to contaminate soil, water and air, generating adverse consequences on the environment and biodiversity. Structural risks arise when leaks have the potential to cause corrosion and damage to the system structure, posing a threat to its integrity. Additionally, there is the potential for ignitions and explosions resulting from material leaks with the risk of widespread damage.

The article by Vílchez et al. (2011) propose an interesting approach to analyse the consequences of loss of containment events involving flammable, toxic, and volatile substances under various operational conditions.

Paper Received: 21 January 2024; Revised: 9 May 2024; Accepted: 27 July 2024
Please cite this article as: Vitale M., Barresi A., Demichela M., 2024, The Use of Aerial Platforms for Identification of Loss of Containment, Chemical Engineering Transactions, 111, 73-78 DOI:10.3303/CET24111013

The study examines several influential factors, including the chemical nature of the released materials, operating conditions, and the effectiveness of safety barriers. The analysis is based on the construction of event trees for various scenarios, allowing a detailed assessment of the possible consequences of a LOC. Two main risk scenarios emerge: the "pool fire" (fire from flammable liquid) and the "toxic dispersion", both with significant implications for the safety of plant personnel and surrounding communities. The importance of considering not only the impacts within the plant but also those on the surrounding communities emerges as an integral part of the analysis.
Therefore, carefully controlling every possible leak in an industrial plant is essential to ensure the safety of people, preserve the operational integrity of the structures, and protect the surrounding environment.

2. Monitoring Loss of containment

Detecting containment leaks can be challenging, especially when the deviation from normal process conditions is subtle and imperceptible. In such situations, it is essential to have early detection systems that act as advance warning. These systems are designed to identify changes in process conditions before the situation develops further. The primary objective of such systems is to assist operators in preventing the propagation of material spills and avoiding the escalation of a potential incident. An example of this is reported in the study by Widarsson and Dotzauer (2008), which highlights the importance of early warnings to limit the damage and the consequences of a possible loss of containment.
Several studies propose innovative monitoring systems to detect containment leaks. Panday et al. (2021) introduced a methodology based on a material balance between the inlet and outlet of the plant to identify and locate leaks. Then, by setting a heat balance, you can identify when the leak began. Widarsson and Dotzauer (2008), however, used Bayesian networks to evaluate losses, allowing the calculation of the release probability in relation to operating conditions. Zhang et al. (2015) adopted a methodology based on acoustic theory to evaluate the location of leaks, establishing a correlation between the delay time of the sound signal and the distance between the microphone and the exact location of the fault. Burgués and Marco (2020) explored the types of sensors to be installed on aerial platforms for the detection of gaseous chemicals, thus providing a solution for monitoring air pollutants.

2.1 Aerial platforms for monitoring

In the process industry, monitoring can be conducted through two analytical methodologies: monitoring large areas over time and instantaneous inspection. The control of large areas over time involves continuous surveillance of these, allowing any change in the site to be detected. This approach, which compares conditions day by day or at predefined time intervals, offers a broader view but with lower precision. Instant inspection, conversely, permits immediate examination of specific site points with high precision, offering detailed, real-time information on the current state of the area of interest. Several studies have implemented the above-mentioned methodologies, both to support precision agriculture with the aim of maximizing yields (Murugan et al., 2017) and for site monitoring where containment losses are possible (Watremez et al., 2018).
Aerial platforms, such as drones, satellites, and airplanes are the main devices for carrying out this monitoring. The methodology, which uses devices capable of moving in the air, offers a perspective from above, facilitating the collection of data and information over large areas or in difficult-to-access environments. The use of aerial platforms for monitoring presents several advantages, including timely acquisition of information, flexibility in operations, and the ability to explore otherwise inaccessible places (Pillosu, 2020). Drones represent the most flexible and versatile platforms for monitoring. They can cover limited areas, which results in greater precision and resolution of the data collected. The drones are piloted from the ground by an operator, who can program the flight plan in advance or adjust the direction, altitude, and speed during the flight itself. This control capability offers significant flexibility in tailoring monitoring operations to the specific needs of each situation. The use of drones requires the installation of a device capable of collecting information. This device, known as a sensor, for the detection of gases aims to:

- Calculate the concentration of gas in the atmosphere. To obtain such data, the drone must fly close to the dispersed gas, allowing the sensor to calculate its quantity. Different studies have adopted this type of sensor to evaluate the concentration of chemical substances. Burgués et al. (2019), for example, use MOX (metal oxide semiconductor) sensors to calculate the concentration of ethanol present in a controlled environment. Koval et al. (2017), on the other hand, employ a catalytic sensor for methane detection.
- Identify released gases or small, difficult-to-detect fires by capturing photos and/or videos from a safe distance. This methodology is particularly suitable for flammable or corrosive substances that could damage or compromise the correct functioning of the equipment.

Recent studies have also implemented these platforms in the industrial sector, both for visual analyses (Casabona, 2020) and for the detection of gaseous leaks. Burgues et al. (2022) employed a drone equipped

with an “electronic nose” to identify odors emitted from different sources present in wastewater treatment plants. Similarly, Barchyn et al. (2019) used drones to detect methane leaks in hydrocarbon production infrastructures, exploiting such screening technologies for their greater efficiency and lower costs compared to traditional methods. Yang et al. (2018) also adopted this methodology to detect methane leaks, employing a system composed of three main technologies: a mini-RMLD (miniaturized Remote Methane Leak Detector) based on tunable diode backscattering laser absorption spectroscopy (TDLAS), a drone autonomous quadcopter, and simplified quantification and localization algorithms. Druart et al. (2021) employed a drone-mounted infrared camera to identify methane leaks from a storage tank. The test was conducted at three different flight altitudes: 80 m, 40 m, and 20 m, with gas losses of 200 g/s, 10 g/s, and 1 g/s. The results of the study (in Figure 1) showed that even at an altitude of 80 m even the smallest methane leaks can be clearly detected.
This type of monitoring offers advantages in terms of speed in real-time data acquisition, ability to identify gas leaks in complete safety conditions and possibility to quantify the concentration of such leaks. Not all cameras are suitable for this analysis; they must have an optical filter with the capability to absorb the spectral bands of the target fluid. Li et al. (2023) identified gaseous clouds using a multispectral camera. The study monitored emissions of NH_3, SF_6, CH_4 and SO_2 (Figure 2) at a distance of 50 m, demonstrating that a monitoring system based on a multispectral infrared camera is capable of detecting gases at long distances, in the order of tens of meters up to one kilometer.

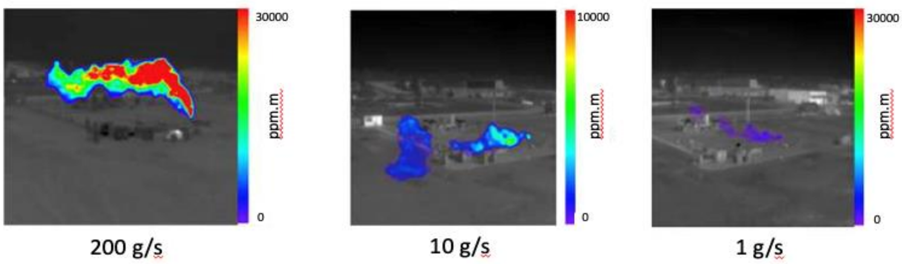

Figure 1: Detection and quantification of methane leaks. Data collection took place, from right to left, at 20 m, 40 m, and 80 m height (Images taken from Druart et al., 2021).

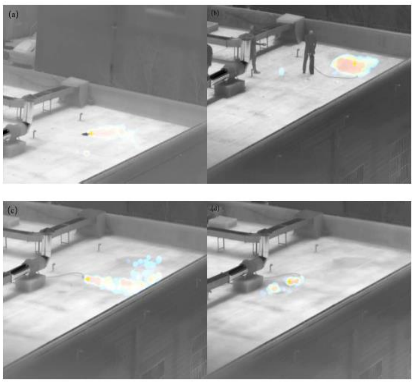

Figure 2: Findings from gas detection using a multispectral camera: (a) Ammonia (NH_3); (b) Sulfur hexafluoride (SF_6); (c) Methane (CH_4); (d) Sulfur dioxide (SO_2) (Image taken from Li et al.,2023).

Watremez et al. (2018) identified a methane cloud using a high-resolution hyperspectral camera and an infrared camera, managing to identify the cloud at a distance of 100 m and calculating its concentration. The study was completed with the use of a LIDAR, an absorption laser used for the measurement of atmospheric gases, capable of quantifying their flow rate.

3. Case study

This research focuses on the analysis of hydrogen, a promising gas for reducing environmental pollution and reducing the use of fossil fuels. Currently, this gas is of great interest since it generates only water as combustion product. Nonetheless, a difficulty linked to hydrogen lies in its small molecules, increasing the likelihood of their escape from the equipment. Furthermore, this element has a wide flammability range, between 4% and 75%,

and a low minimum ignition energy value, equal to 0.017 mJ (Eh et al., 2022). Therefore, in the event of a leak, the hydrogen is likely to form flammable mixtures with air that can easily ignite, generating jet fires that are difficult to see in daylight. This underscores the need for continuous and real-time monitoring to guarantee safety in plants and distribution networks that contain hydrogen.
It is crucial to note the limitations of traditional fuel sensing technologies, such as infrared and catalytic bed sensors, in the specific context of hydrogen. While infrared and catalytic bed sensors are widely used to detect other fuels in air, hydrogen cannot be effectively identified via infrared radiation, making this technology inadequate. Catalytic bed sensors, even when used for other gases, have limitations for detecting hydrogen leaks at safe distances, as they require direct contact with the leaking gas. This approach could expose equipment to risks related to flammable or corrosive substances, underscoring the need for safe and more effective alternatives.
Wang et al. (2022) conducted experiments to validate the fluid dynamic model, employing the Schlieren method and supported by a high-speed camera, as shown in Figure 3. During these experiments, they focused on detecting hydrogen leaks, illustrating alterations in the hydrogen-flow morphology as stagnation pressure rises.

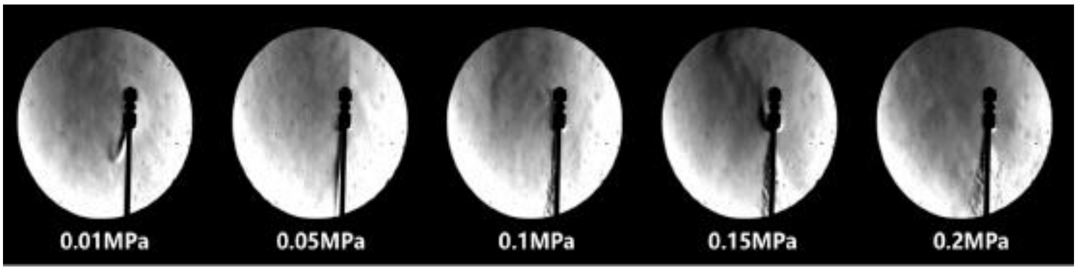

Figure 3: Schlieren method for hydrogen leaks at different pressure in the pipeline upstream of the leakage outlet P=0.01; 0.05; 0.1; 0.15; 0.2 MPa (Image taken from Wang et al., 2022).

The figure depicts the hydrogen gas flow, with a greys-scale gradient indicating its behaviour. Below 0.1 MPa, the flow shows a momentum-dominated downward jet, transitioning to an upward buoyancy-dominated process. At 0.05 MPa, the downward jet is laminar, while above 0.1 MPa, turbulence emerges as hydrogen entrains air. Beyond 0.15 MPa, the jet exhibits a "tail-sweeping" turbulent flow around the stainless-steel pipe, attributed to atmospheric pressure influencing the hydrogen flow.
Despite efforts to simulate the behaviour of hydrogen through mathematical models, there appears to be a lack of specific studies on the detection of real-scale hydrogen leaks in industrial plant contexts. The implementation of large-scale hydrogen leak detection technologies could play a key role, given the growing importance of hydrogen as a sustainable resource (Elaoud et al., 2010).
The lack of research in this specific domain provides a chance to fill a void and develop effective solutions for monitoring and reducing hydrogen losses in industrial environments. Prioritizing safety is crucial, particularly when handling fuels such as hydrogen, and prompt leak detection is essential for sustaining a safe workplace and preventing potential accidents. The utilization of drones equipped with cameras emerges as a ground-breaking solution to tackle the issue of hydrogen leaks on an actual scale. This technological advancement enables real-time leak detection and precise identification of failure points, offering an effective and swift approach to the surveillance of industrial facilities.
A crucial challenge associated with the use of drones is selecting the most suitable sensor for the safe detection of this gas. A hydrogen detector, such as a MOX sensor or an electronic nose, may not be enough, considering that hydrogen leaks in industrial plants can easily cause jet fires. Using a sensor that requires direct contact with the gas could compromise the safety of the flight, risking damage to the equipment. Two strategies are proposed to address the identified problem:

- **Schlieren Method for Gas Detection**: The Schlieren method is an optical technique designed for gas detection, leveraging density variations in a transparent medium. This method allows for the visualization and recording of gas flows. Within this approach, density fluctuations in the gas induce the bending of light rays, resulting in distinctive patterns referred to as Schlieren lines or density shadows. Utilizing a sensing system, such as a high-sensitivity camera mounted on a drone, enables the capture of changes in light intensity within these density shadows (Hargather and Settles, 2012). The resultant images effectively highlight variations in gas density, providing visual cues for the identification of leaks or flows. This real-time monitoring capability is essential for ensuring prompt detection and response.

- **Thermal Camera Detection of Hydrogen Leaks**: Given the low minimum ignition energy and high heat of combustion of hydrogen, the release of hydrogen can easily lead to jet fires, producing a substantial amount of heat. This phenomenon can be efficiently detected using a thermal camera installed on a drone. By employing thermal imaging, real-time monitoring of hydrogen leaks becomes feasible. The thermal camera can detect the temperature anomalies associated with hydrogen release, facilitating the swift identification of potential leaks, and enhancing overall monitoring capabilities.

A further element to take into consideration is the flight height of the drone, it is essential to establish an optimal distance to ensure a risk-free flight. Several studies have examined the behaviour of hydrogen losses to define a concentration profile in time and space. Gong et al. (2022) conducted a simulation to model the hydrogen release, investigating the concentration profile of the leak. Through this approach, they successfully identified a correlation between concentration levels C_{H_2} (% Vol) and the distance from the release point *x*, depending on the exit hole diameter *D*, the density of the ambient air ρ_a and the density at the nozzle ρ_0:

$$\frac{1}{c_{H_2}} = 0.000188\left(\frac{x}{D}\right)\sqrt{\frac{\rho_0}{\rho_a}} + 0.0064 \tag{1}$$

From expression 1 it is possible to derive the safety distance, which is the minimum recommended or necessary distance to ensure safety, beyond which the hydrogen concentration decreases below 4% (lower flammability limit). To guarantee a safe flight, the Ministerial Decree n. 151 of 9 May 2001 (Ministero dei Lavori Pubblici, 2001) was followed, which establishes the threshold value of lethality onset at a concentration of 2%, the half of the lower flammability limit in the event of a jet fire. This led to the following expression:

$$x_{2\%} = 2625{,}53D\left(\frac{\rho_a R_{H_2} T}{P}\right)^{-0.5} \tag{2}$$

where *T*, *P*, and R_{H2} are the temperature and pressure at the nozzle, and the hydrogen constant, respectively. This formula will aid in determining the minimum distance at which it is safe to let the drone fly without compromising the integrity of the equipment.

4. Conclusion

Nowadays, careful monitoring of possible content leaks is essential to prevent potential harm. Different research methodologies are aimed at monitoring leaks, and some make use of experimental visual data, such as photographs and videos, with the help of aerial platforms.
Interest in hydrogen as an energy carrier is growing; the challenge with this gas lies in its extremely small molecules, which can easily escape from tanks and pipelines. This review suggests two technologies for promptly detecting hydrogen leaks from process plants or distribution lines. The Schlieren method is an optical technique for gas detection, utilizing density variations in a transparent medium to visualize and record gas flows. Otherwise, the use of thermal imaging, such as the thermal camera, can identify temperature anomalies associated with hydrogen release. Both approaches can be executed utilizing a drone, enabling real-time data collection and coverage of hard-to-reach areas. An expression of the distance at which hydrogen reaches a concentration of 2% from the exit point of the equipment was explored to identify a safe flight distance. The subsequent phases of our research will involve the implementation of the proposed technologies.

Acknowledgments

Part of this study was carried out within the RETURN Expanded Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investiment 1.3 – D.D. 1243 2/8/2022, PE0000005).

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