CHEMICAL ENGINEERING TRANSACTIONS

VOL. 36, 2014

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216

DOI: 10.3303/CET1436006

Detection and Localization of Leakages in Toxic/Flammable Chemicals Pipelines Using Distributed Fibre Optic Sensor

Rob de Bont[a], Daniele Inaudi[b], Roberto Walder*[b]

[a]Yara, Zone Portuaire, 44550 Montoir de Bretagne, France
[b]Smartec SA, Via Pobiette 11, 6928 Manno, Switzerland
roberto.walder@smartec.ch

Over the past decades, several major industrial accidents led the chemical industries handling large quantities of dangerous substances and national regulation bodies to reinforce the safety and prevention measures of their installations, in compliance with local laws such as the Seveso II directive in Europe. Indeed, leakages of chemicals can be at the origin of toxic releases, which can have severe consequences on the installations as well as on the environment and nearby inhabitants. Industries are prompted to take all possible measures to reduce the occurrence of such catastrophic events by implementing additional technical safety barriers in order to prevent or mitigate any potential danger on their key structures such as pipelines, reactors, storages, transfer lines, etc.

Pipeline leakages may have different origins, such as corrosion, fatigue, material flaws, shocks, abnormal temperatures, extreme pressures, or excessive deformations caused by ground movement. In the case of liquefied or pressurized gases, leakages can be detected by the rapid drop of temperature due to the evaporation of the released liquid and its evaporation gases or due to gas expansion. These local thermal anomalies can be reliably detected by a fibre-optic distributed temperature sensing system able to detect temperature changes of the order of 1 °C, with 1m spatial resolution and 10 s response time. A fibre optic cable is installed all along the whole length of the pipeline and is connected to a measurement system that can automatically detect temperature anomalies which are tell-tale of leakages and generate an alert to initiate appropriate response actions on the affected pipeline section. Such a system has been permanently deployed at several industrial and chemicals sites were functional and operational tests have also been carried out.

This paper will present the system architecture and installation at an ammonia production, storage, shipping and processing site. Results of simulated leakage detection tests and long-term operation in normal conditions will also be presented.

1. Introduction

Chemical leaks, such as ammonia, can be the origin of toxic releases. These releases can have severe consequences on the installations as well as on the environment and nearby inhabitants. Industries are prompted to take all possible measures to reduce the occurrence and the consequences of such events by implementing additional safeguards (Fabiano B., Currò F., 2012; Papadakis G.A., Porter S., Wettig J., 1999). The tragic consequences of the September 2001 accident in Toulouse make it clear that risks had been underestimated - both from the point of view of safety management and urban planning. In the case of safety management, the controls to prevent such a catastrophic event were insufficient or inadequate. Since the Toulouse incident, the legislation in France is much more detailed in the following ways: all risks with toxic gases and liquids must be evaluated including 100 % of the line size (i.e., a guillotine pipe rupture), a 10 % equivalent of the diameter leak, and a 1 % opening. The duration of the release scenarios vary from some seconds to at least 30 min.

To illustrate the importance of detecting small and medium-sized leaks, let's consider the following example. In a French fertilizer production plant far more than 200 possible leak or loss of containment

Please cite this article as: de Bont R., Inaudi D., Walder R., 2014, Detection and localization of leakages in toxic/flammable chemicals pipelines using distributed fibre optic sensors, Chemical Engineering Transactions, 36, 31-36 DOI: 10.3303/CET1436006

scenarios (NH_3, NO_x) have been documented. Each situation is studied with a fault tree analysis and HAZOP. Table 1 is an extract of a French SEVESO safety study for illustration of one scenario.

Table 1: Risk analysis for different leak scenarios

Flow of NH_3 spill	***% of pipeline flow***	***Spill duration (min)***	***Toxic cloud distance with risk of fatalities (m)***
~200 kg/s	100% (full rupture)	1	170
~40 kg/s	10%	1	160
~40 kg/s	10%	30	**465**
~4 kg/s	1%	30	125

The scenario represented in Table 1 is relative to unloading anhydrous ammonia at 750 t/h (P = 3.5 bar, T = -33 °C), through a 300 mm diameter pipeline, with typical weather conditions. The last column indicates the maximum distance from the leak where fatalities can be expected. It is not the goal of this paper to develop the causes which might contribute to loss of containment and how to avoid any accident. The goal here is how to detect and stop the release as quickly as possible. Consider the following:

- A guillotine pipe rupture is easily detected by the process (measurement of flow or pressure) and automatic emergency shut-down of the installation is immediate.
- Smaller leaks, like a 10 % scenario, are not detected by the regular process instruments.
- A 30-min release is a typical scenario when NH_3 detection is delayed because ammonia gas detectors might be too far or not exactly in the right wind direction. In other cases, the detection of the release is dependent on operators who may not be in the area for some time, or the cloud could get undetected because the leak occurs at night.

This examples, shows that the most dangerous scenario in terms of distance reached by the toxic cloud is a 10% leak that is undetected for 30 min. there is therefore a real need to identify a detection system that is capable of reducing the detection time in such situation down to less than 1 min.

2. Fibre Optic Distributed Temperature Sensing

2.1 Sensing Principles

Recent developments of distributed optical fibre temperature sensing techniques provide a cost-effective tool that allows monitoring over long distances (some km) with high spatial resolution (typically every meter). Using a limited number of very long sensors it is now possible to monitor the behaviour of pipelines with a high measurement speed at a reasonable cost (Inaudi D., Belli R., Walder R., 2008; Inaudi D., Glisic B., Figini A., Walder R., 2007). In this case we would talk of a distributed sensing system with a range of 30 km and a spatial resolution of 1 m. Systems based on Raman scattering typically exhibit a temperature resolution of the order of 0.1 °C with measurement scan times as low as 10 seconds. Figure 1 shows an example of temperature sensing cable. Figure 2 pictures a typical user interface, able to identify multiple leak locations on a map of the site.

2.2 Leak Detection

The basic principle of pipeline leak detection through the use of distributed fibre optic sensing relies on a simple concept - when a leak occurs at a specific location along the pipeline, the temperature distribution around the pipeline changes. This change in temperature is localized both in space (a few meters around the leak location) and in time (the onset of the leak). This makes the algorithmic detection of leaks relatively easy to implement. The origin of the temperature disturbance around the pipeline depends on the type of pipeline and its surroundings.

In the case of ammonia leaks from above-ground pipelines, the main effects are the following:

- The liquid component of the ammonia leak drops to a temperature of -33 °C and wets the sensing cable directly through dripping, splashing and spraying, provoking a fall in the recorded temperature.
- The gaseous component of the ammonia leak forms a cold plume that also cools down the sensing cable.
- Part of the gaseous component of the ammonia leak condenses on the pipe and cable surface, producing an additional liquid phase
- The leak also produces a drop in temperature of the pipeline itself that is transmitted to the sensing cable.

Figure 1: Distributed temperature sensing cable

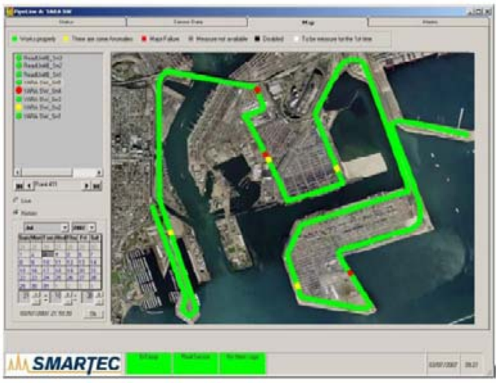


Figure 2: Example of user interface showing location of multiple events, e.g. leaks

3. Technology Validation

Short- and long-term tests and experiments were carried out to validate the technology for ammonia leak detection and for its compatibility with real-life fertilizer plant environments.

3.1 On-Site Leak Simulations

Several tests were performed on-site at the Yara plant in Le Havre, France. These tests consisted of pouring liquid ammonia on pipelines equipped with an optical fibre sensor and verifying the temperature drop measured by the system. Typically, 1 kg of ammonia was poured on a pipe section of 0.5 m over the duration of 1 min (see Figure 3).

Figure 3: Ammonia pouring test setup

Figure 4 shows the temperature drop recorded by the measurement system at the leak location. Temperature drops of 5 °C over 20 s and 10 °C over one minute were recorded in all tests. This response can differentiate between the normal temperature changes that occur when the line is put into service for a product transfer in the following ways:

- The rate of temperature change from the leak is higher than the one recorded during the initiation of ammonia transfer.
- The operational changes, such as initiation of ammonia transfer, of temperature affect long sections of the pipeline uniformly, whereas the leaks only affect a small portion of the pipeline.

Tests were also performed on pipelines covered with ice, showed that the ammonia quickly melts the ice and comes into contact with the sensing cable (initially covered by ice itself).

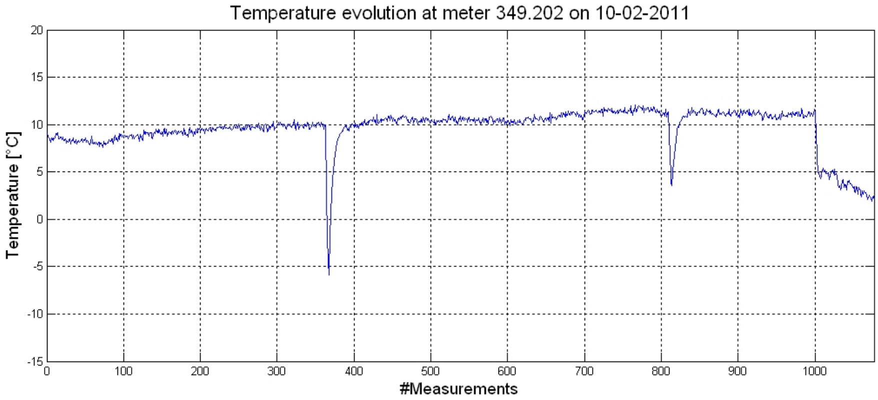


Figure 4: Temperature drop recorded during two ammonia leak tests and a pipeline restart

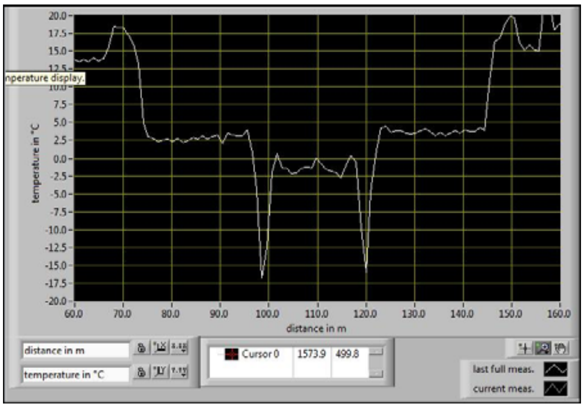
3.2 Laboratory Leak Simulations

In a series of laboratory experiments carried out at the French INERIS laboratory (part of the French Ministry of Environment), the performance of the system was evaluated in the presence of a real leak from a pipeline. These tests were necessary to verify the field test results – that is, the necessary temperature drop would also be produced in real leak conditions.

The experiment consisted of a pipeline section including a cut with an equivalent section of 5 %. The pipe contained anhydrous ammonia at 7 bar and the cut produced a leak of 38-45 g/s after opening the quick-release plug. High-speed and infrared cameras were used to capture the dynamics of the leak and the resulting temperature changes. Both vertical and lateral leaks were tested with the cable placed under the pipeline.

The experiment showed a very quick temperature drop of more than 10 °C/min that was easily detected by the system. The high-speed video images, showed no significant spray or dripping of ammonia on the cable, therefore the temperature drop was attributed mostly to the ammonia gas cloud and its re-condensation and evaporation on the pipe and on the sensing cable.

The two drops of temperature clearly visible in Figure 5, taken approximately 20 s after the release starts, are due to the loop configuration used for the sensing cable. The cable passes twice in the leak zone, on its way out and on its way back to the instrument.



distance in m
temperature in °C
Cursor 0 1573.9 499.8

Figure 5: Plot of temperature as a function of distance during leak test

3.3 Performance without Leaks

To evaluate the temperature variations occurring during normal plant operations, without ammonia leaks, a sensing system was installed on a transfer pipeline used to refill trucks. This type of pipeline is subject to frequent and sudden temperature changes due to the start-and-stop nature of these operations. This scenario creates complex temperature patterns compared to the constant flow in a production transfer line.

A test period spanning summer and winter seasons, collected data every 10 s over 250 m of a pipeline was considered. The data was analysed statistically and it was found that the maximum temperature variation between two measurements was 2.5 °C well below the rapid changes observed in the case of a leak. It is therefore possible to operate such a system without triggering false alarms in normal operational conditions.

Figure 6 shows the tests results, including a leak simulation test performed at the end of the test period that clearly exceeded the threshold.

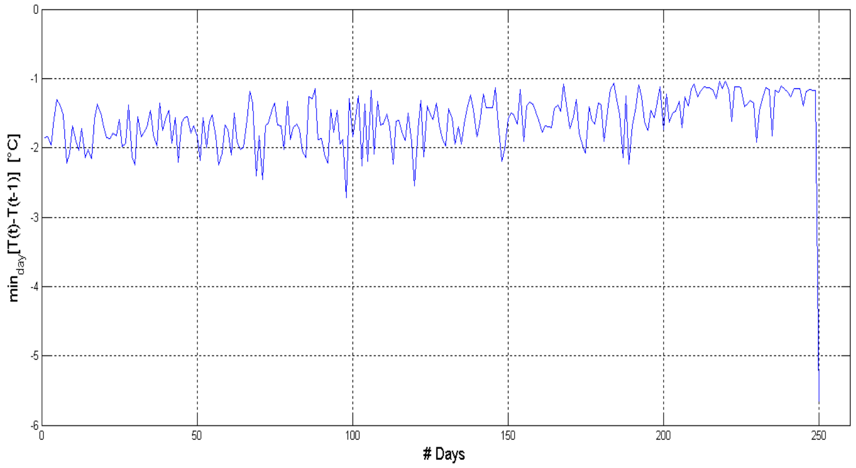


Figure 6: Maximum daily rate of change with-out leaks and with a leak test at the end

4. Recommendations

The following recommendations are based on the knowledge accumulated during the laboratory and field tests. They serve as a starting point for the implementation of such an ammonia detection system in a plant.

4.1 Cable Installation on Different Types of Pipelines

The cable installation procedure aims at maximizing the probability of detection. It is recommended to install the cable(s) in a way to increase the likelihood of contact with the leaking liquid ammonia and the resulting gas cloud. To maximize the likelihood of detection we make the following recommendations:

- In the case of horizontal pipeline sections installing the cable at the bottom of the pipeline and attach it with ties to the pipe every 50 cm. The cable does not need to be in contact with the pipe along its whole length, since it will catch dripping liquid ammonia and the cold ammonia gas.
- For vertical sections install the cable in a spiral with a pitch of 1 m in order to catch any down flow of ammonia.

These recommendations are also valid for insulated pipelines, where the sensing cable can be installed outside the insulation cover in the same positions.

Additional pipeline elements such as valves, splits and pumps require specific installation schemes that exceed the scope of this publication.

4.2 Performance of Data Acquisition Unit

Based on the test results and the experience gathered on several plants in France and Italy we recommend the following configurations, minimum performance and testing stings for ammonia leak detection. The laboratory and field analysis show that with this configuration it is possible to detect a 10% leak within 20s, and a small leak of 50 g liquid NH_3 /s in about 1 min.

The minimum configuration (without redundancy) is as follows:

- 1 data acquisition system with 2 channels
- Measurements scan time of 10 s per channel
- Temperature resolution of 0.5 °C for 10 s measurement scan time
- Spatial resolution of 1 m
- Cable configuration consisting of a single cable with 4 optical fibres, 2 fibres connected at the far end to form a loop connected to the two interrogator channels
- Automated Trip Testing System (ATTS).

The ideal configuration, which includes redundancy, is as follows:

- 2 Data acquisition systems with 2 channels each
- Measurement scan time of 10 s per channel
- Temperature resolution of 0.5 °C for 10 s measurement scan time Spatial resolution of 1 m
- Cable configuration consisting of two cables with 4 optical fibres each with the two cables connected at the far end to form a loop. Each loop connected to the two channels on each interrogator.
- Voting system (see next paragraph)
- Automated Trip Testing System (ATTS).

4.3 Reliability and Confidence Level

An ammonia leak detection system is likely to sit idle for all its life, hopefully never detecting any real leak. Idleness presents a challenge for reliability. The system will be “forgotten” most of the time, and it is difficult to guarantee that it will perform perfectly the day it is really needed. Ensuring and certifying a high confidence level becomes imperative in these conditions.

Since it is difficult to frequently carry out leak simulations on the line to verify the system response, we have developed a device that can carry out such tests in a fully automated way. The Automated Trip Testing System (ATTS) is a device, fully independent of the data acquisition system, which can create an artificial leak along the sensing cable. In so doing, the correct response of the system and alarms can be verified. The ATTS uses a Peltier cell to cool a 2 m section of optical fibre at a rate similar to the one observed in the case of ammonia leak. The system observes the signal coming from the relay module to verify alarm triggering. A dedicated relay is allocated to the ATTS fibre section, so that the alert in this zone does not trigger any pipeline shutdown sequence, is not transmitted to the operator, but is recorded in the plant event log. The ATTS is placed at the end of the fibre loop, so that the integrity of the whole fibre can be verified in one test. Typically, a leak simulation can be simulated every hour, so that thousands of tests are carried out every year.

If multiple redundant reading units are used, it becomes possible to increase both availability and system reliability by using a voting system on the relay outputs. We recommend using a 2oo2 (two out of two) configuration and implement a fall-back to 1oo1 if one system is unavailable.

4.4 Detection Algorithms and Thresholds

Based on the tests results and field experience, we recommend the following initial settings for ammonia leak detection:

- An absolute temperature threshold set at the average pipe temperature -20 °C
- Rate of change thresholds of -3 °C/10 s and -12 °C/1 min

It is suggested to carry out a test period including summer and winter to adjust the thresholds before using the system as part of an automated safety loop.

5. Conclusions

This system is deployed at several industrial sites including Yara France, GPN & Borealis. This technology significantly contributes to improve process safety for the following reasons:

- Fibre optic cable system developed by SMARTEC SA is able to provide early detection of small ammonia leaks.
- The technology is equipped with an Automatic Test and Trip System to increase reliability.
- Functional and operational tests, in association with INERIS, have been carried out and have demonstrated that leak rates less than 50 g liquid NH_3 /s can be detected in about 20-30 s anywhere along the whole pipeline. This sensitivity exceeds the requirement and expectations identified in the process safety the risk studies.

References

Fabiano B., Currò F., 2012. From a survey on accidents in the downstream oil industry to the development of a detailed near-miss reporting system, Process Safety and Environmental Protection, 90, 357-367.

Inaudi D., Belli R., Walder R., 2008, Detection And Localization Of Micro-Leakages Using Distributed Fibre Optic Sensing, 7th International Pipeline Conference, IPC2008, 29th September – 3rd October, Calgary, Alberta, Canada, Paper No. IPC2008-64280, pp. 599-605

Inaudi D., Glisic B., Figini A., Walder R., 2007, Pipeline Leakage Detection and Localization Using Distributed Fiber Optic Sensing, Rio Pipeline Conference 2007, Rio de Janeiro, Brazil, October 2-4

Papadakis G.A., Porter S., Wettig J., 1999, EU initiative on the control of major accident hazards arising from pipelines, J. of Loss Prevention in the Process Industries 12, 85-90.