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PIPELINE LEAKAGE DETECTION AND LOCALIZATION USING DISTRIBUTED FIBER OPTIC SENSING

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Abstract

Distributed fiber optic sensing offers the ability to measure temperatures and strain at thousands of points along a single fiber. This is particularly interesting for the monitoring of pipelines, where it allows the detection and localization of leakages of much smaller volume than conventional volume balance techniques. Sensing systems based on Brillouin and Raman scattering are used to detect and localize leakages in fluid, gas and multiphase pipelines, allowing the monitoring of hundreds of kilometers of pipeline with a single instrument and the localization of the leakage with a precision of 1 or 2 meters. Early applications of this technology have demonstrated that the design and production of sensing cables and their optimal location around the pipeline section are critical elements for the success of any distributed sensing instrumentation project.
This contribution presents advances in distributed sensing and in novel sensing cable design for distributed temperature and strain measurements. The proper installation technique and location around the pipe is discussed for fluid and gas pipelines installed above ground, below ground and offshore. The paper also reports a number of significant field application examples of this technology as well as field tests with controlled leakages.

1. Introduction

Flowlines – pipelines or gas-lines often cross hazardous environmental areas, from the point of view natural exposures such as landslides and earthquakes, and from the point of view of third party influences such as vandalism or obstruction. These hazards can significantly change the original functioning of the flowline, leading to damaging, leakage and failure with serious economic and ecologic consequences. Furthermore, the operational conditions of the pipeline itself can induce additional wearing or even damage due to corrosion, erosion and fatigue.
The structural and functional monitoring can significantly improve the pipeline management and safety. Providing regularly with parameters featuring the structural and functional condition of the flowline, monitoring can help (1) prevent the failure, (2) detect in time the problem and its position and (3) undertake maintenance and repair activities in time. Thus the safety is increased, maintenance cost optimized and economic losses decreased. Typical structural parameters to be monitored are strain and curvature while the most interesting functional parameters are temperature distribution, leakage and third-party intrusion. Since the flowlines are usually tubular structures with kilometric lengths, structural monitoring of their full extent is an issue itself. The use of the discrete sensors, short- or long-gage is practically impossible, because it requires installation of thousands of sensors and very complex cabling and data acquisition systems, raising the monitoring costs. Therefore, the applicability of the discrete sensors is rather limited to some chosen cross-sections or segments of flowline, but cannot extend to full-length monitoring. Other current monitoring methods include flow measurements at the beginning and end of the pipeline, offering an indication of the presence of a leak, but limited information on its location.
Recent developments of distributed optical fiber strain and temperature sensing techniques based on Raman and Brillouin scattering provide a cost-effective tools allowing monitoring over kilometric distances. Thus, using a limited

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number of very long sensors it is possible to monitor structural and functional behavior of flowlines with a high measurement and spatial resolution at a reasonable cost.

Unlike electrical and point fiber optic sensors, distributed sensor offer the unique characteristic of being able to measure physical and chemical parameters along their whole length, allowing the measurements of thousands of points using a single transducer. The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. Both systems make use of a nonlinear interaction between the light and the silica material of which the fiber is made. If light at a known wavelength is launched into a fiber, a very small amount of it is scattered back at every point along the fiber. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are different form the original signal (called the Raman and Brillouin components). These shifted components contain information on the local properties of the fiber, in particular strain and temperature. Figure 1 shows the main scattered wavelengths components for a standard optical fiber. It can be noticed that the frequency position of the Brillouin peaks is dependent on the strain and temperature conditions that were present at the location along the fiber where the scattering occurred, while the intensity of the Raman peak is temperature dependent.

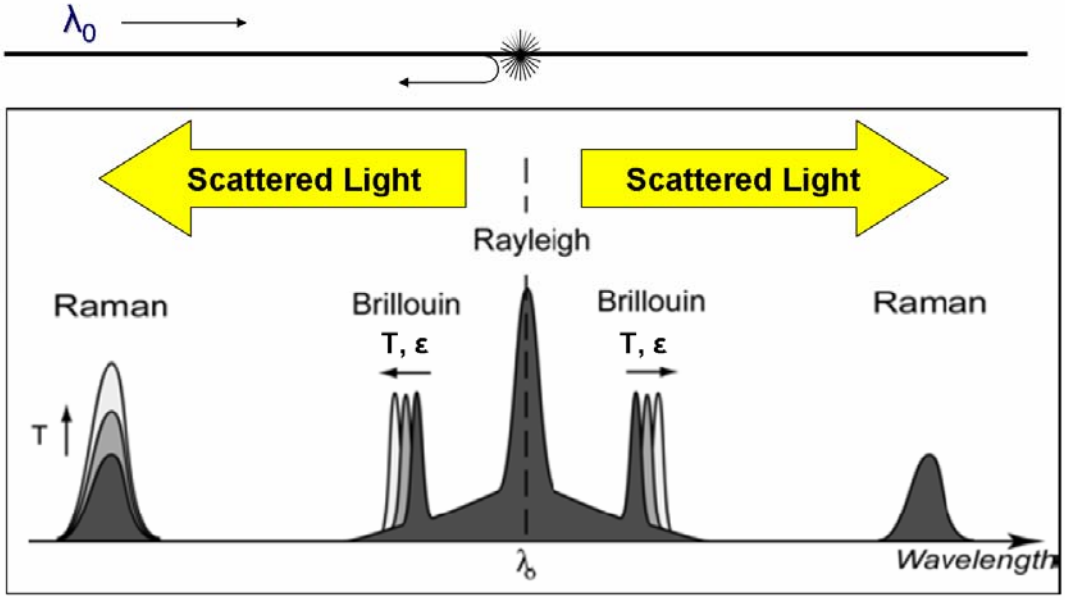

Figure 1. Light scattering in an Optical Fiber

When light pulses are used to interrogate the fiber, it becomes possible, using a technique similar to RADAR, to discriminate different points along the sensing fiber by the different time-of-flight of the scattered light. Combining the radar technique and the spectral analysis of the returned light one can to obtain the complete profile of strain or temperature along the fiber. Typically it is possible to use a fiber with a length of up to 30 km and obtain strain and temperature readings every meter. In this case we would talk of a distributed sensing system with a range of 30 km and a spatial resolution of 1 m.

Raman scattering is the result of a nonlinear interaction between the light traveling in a fiber and silica. When an intense light signal is shined into the fiber, two frequency-shifted components called respectively Raman Stokes and Raman anti-Stokes will appear in the backscattered spectrum. The relative intensity of these two components depends on the local temperature of the fiber. Systems based on Raman scattering typically exhibit a temperature resolution of the order of 0.1°C and a spatial resolution of 1m over a measurement range up to 8 km.

For temperature measurements, the Brillouin sensor is a strong competitor to systems based on Raman scattering, while for strain measurements it has practically no rivals. Brillouin scattering is the result of the interaction between optical and sound waves in optical fibers. Thermally excited acoustic waves (phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light propagating in the fiber is diffracted backward by this moving grating, giving rise to a frequency-shifted component by a phenomenon similar to the Doppler shift. The most interesting aspect of Brillouin scattering for sensing applications resides in the temperature and strain dependence of the Brillouin shift. This is the result of the change the acoustic velocity according to variation in the silica density. The best Brillouin scattering systems offer a temperature resolution of 0.1°C, a strain resolution of 20 με and a measurement

range of 30 km with a spatial resolution of 1 m. The systems are portable and can be used for field applications. Figure 2 shows an example of a Raman and a Brillouin interrogator.

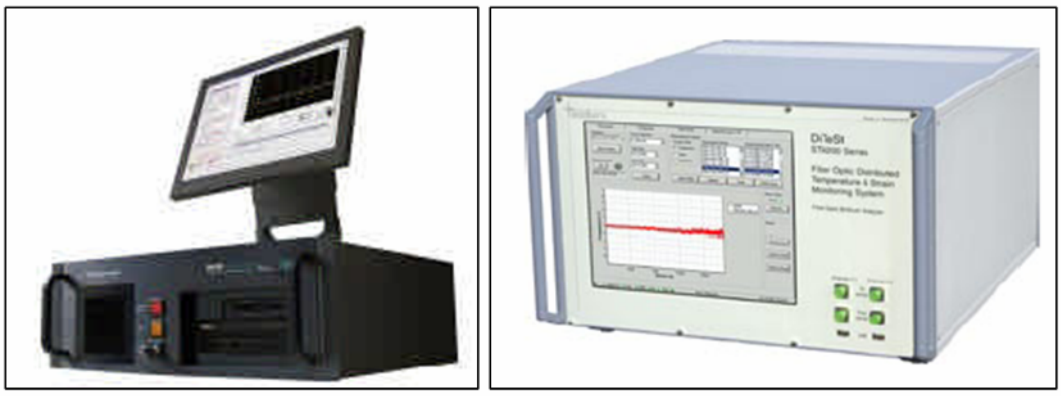

Figure 2. Raman and Brillouin distributed sensing interrogators.

Since the Brillouin frequency shift depends on both the local strain and temperature of the fiber, the sensor design will determine the actual sensitivity of the system. For measuring temperatures it is necessary to use a cable designed to shield the optical fibers from an elongation of the cable. The fiber will therefore remain in its unstrained state and the frequency shifts can be unambiguously assigned to temperature variations. Measuring distributed strains also requires a specially designed sensor. A mechanical coupling between the sensor and the host structure along the whole length of the fiber has to be guaranteed. To resolve the cross-sensitivity to temperature variations, it is also necessary to install a reference fiber along the strain sensor. Special cables, containing both free and coupled fibers allow a simultaneous reading of strain and temperature. Figure 3 shows examples of temperature, strain and combined cables.

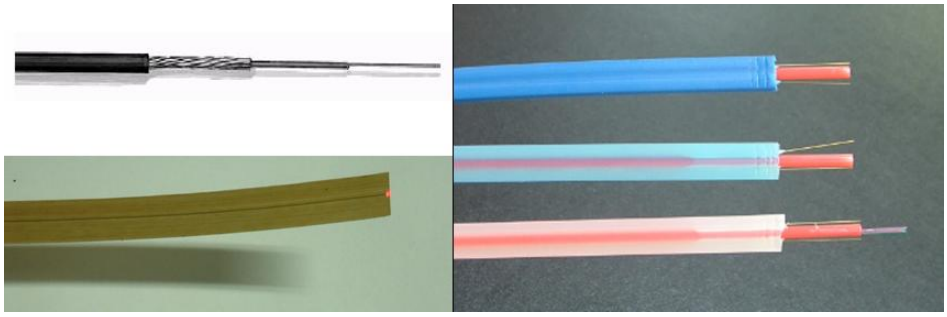

Figure 3. Sensor Cable for Temperature, Strain and combined Strain and Temperature.

2. Pipeline Leakage detection

The basic principle of pipeline leakage detection through the use of distributed fiber optic sensing relies on a simple concept: when a leakage 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 leakage 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. The most typical effects are the following:

- The released liquid is warmer than the surrounding soil (typical for buried oil pipelines)
- The released gas produces a local cooling due to pressure release (typical for buried, underwater and surface gas pipelines)
- The released liquid changes the thermal properties of the soil, in particular thermal capacity, and influences the natural day/night temperature cycles.
- A warm plume is formed around the pipeline (typical for underwater oil pipelines)
- In the case of multiphase pipelines a combination of the above can occur.

Knowing the above effects, one can determine the ideal sensing cable placement around the pipeline.

In the case of a buried oil pipeline the best location for the sensing cable is below the pipe, but not in direct contact. At that position there is a maximum probability of collecting the released oil, independently form the leakage location. This is depicted in Figure 4.

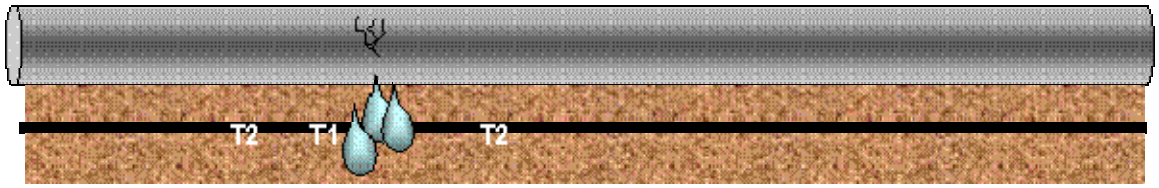

Figure 4. Detection of a liquid leak through a cable placed under the pipeline.

If the pipeline is installed below the water table or underwater, the oil will have a tendency to rise and not to sink. In this case, the ideal placement is reversed.
As we have pointed out, a gas leakage produces a temperature drop at the leak location. This has the tendency to cool down the pipeline itself and its surroundings. The best position for the temperature sensing cable is in this case in direct contact with the pipeline surface. In this case we make use of the good thermal conduction properties of the pipeline itself to transfer the cooling from the leak to the cable. An example of such installation is depicted in Figure 5.

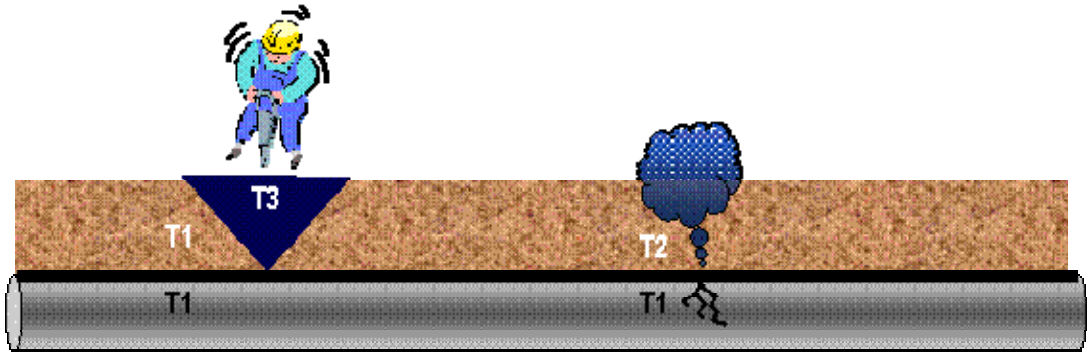

Figure 5. Detection of a gas leak through a cable placed on the pipeline. This arrangement can also be used to detect a third-party intrusion.

This arrangement can also be used to detect an intrusion attempt. When the pipe surface is exposed to the air; this also produces a local thermal change that can be detected by the same cable. In this situation, the best location is obviously above the pipeline.

3. Qualification Tests

In the following sections we will present two qualification tests that were performed to demonstrate the ability of a distributed fiber sensor to detect oil and gas leakages, respectively.

3.1. Oil Leakage simulation

To simulate an oil leakage form a buried pipeline, a test has been performed at the premises of Praoil in Italy, in cooperation with Electronic News. The optical fiber cable, containing two optical fibers, was buried in a small layer of sand at approximately 1.5 m below ground. Successively, a polyethylene pipe was placed above the cable, in a serpentine, and provided with taps allowing a controlled injection of water in the ground. Several taps were installed with varying horizontal and vertical distances to the sensing cable. Each tap was also instrumented with a volume meter to asses the leak volume and capacity. The temperature of the injected water could also be adjusted to simulate different operational conditions. Figure 6 illustrates the testing setup.

Figure 6. Leakage detection simulation arrangement. Warm water is injected in the ground at different positions with respect to the sensing cable positions. Several taps, with volume meters are used to generate controlled leaks.

In a first testing session, four leakages were produced in sequence at different location. The following table summarizes the leaks.

Table 1. Test program

TIME	*TAP*	*FLOW RATE [l/min]*	*LEAKAGE VOLUME [m^3]*
15.12	D1 opening	10	0.08
15.20	D1 closing		
15.20	D2 opening	16	0.40
15.45	D2 closing		
15.45	D3 opening	14	0.91
16.50	D3 closing		
17.00	D4 opening	6	0.06
17.10	D4 closing		

The next Figure 7 shows the raw temperature data recorded during the test. Although temperature profiles were recorded every minute, for clarity, we have depicted only one measurement every 10 minutes.

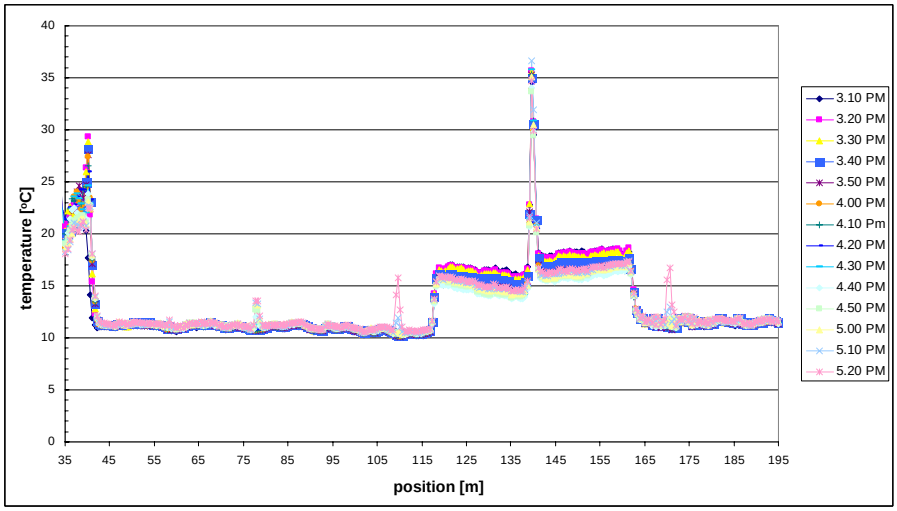

Figure 7. Raw temperature data for the leakage test.

The initial temperature variations, from the beginning of the cable to approximately 38m correspond to a section of the sensing cable above ground and are due to different contact with the ground and sunshine conditions. From meter 38 to 117 the cable is in the ground and its temperature is much more constant, around 12°C. From meter 117 to 158 the cable is again in the air and than re-enters the ground coming back in the opposite direction. The interesting section for the experiment is therefore the one between 38 and 117 meters. In figure 7 it is already possible to observe a couple of temperature peaks at leakage locations, however other leaks are not easily visible and additional processing is therefore necessary.
The first step is to move to a relative visualization, where the temperature is plotted relatively to a reference temperature profile obtained at the beginning of the test. Once this is done, we obtain the results shown in Figure 8. All four leakages are now clearly visible. It has to be noticed than the fist leakage was in the transition zone between buried and exposed section of pipe and cable.

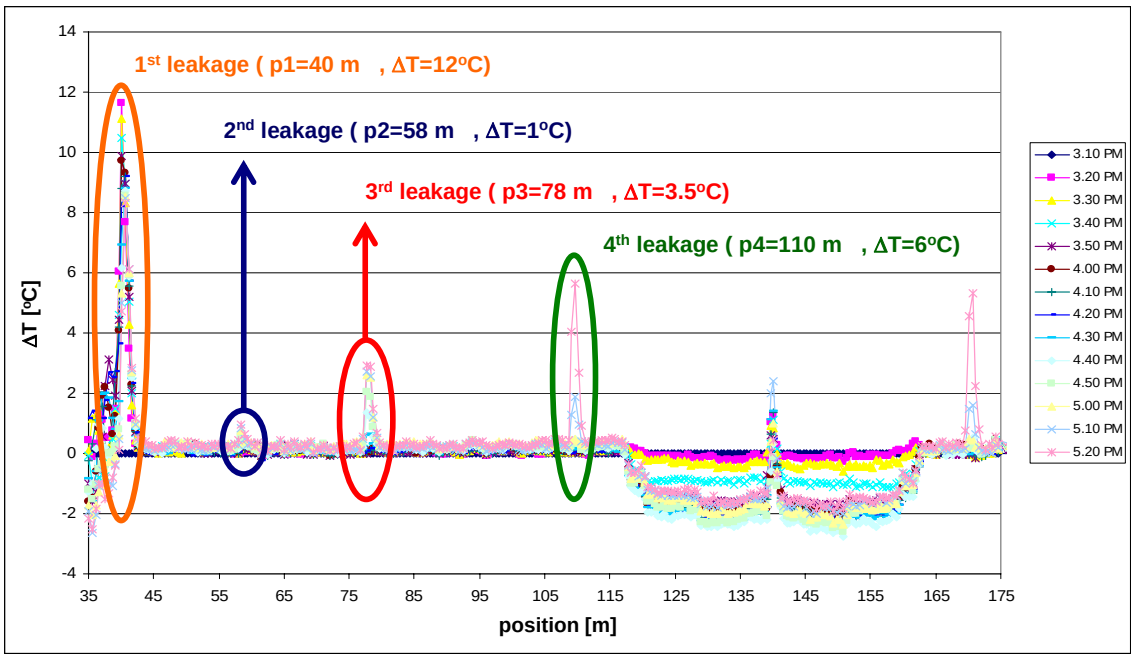

Figure 8. Relative temperature data for the leakage test.
The temperature peaks from the four leakages are clearly visible.

In order to quantify the detection time and released volume we will now concentrate on a single leak and observe the associated temperature evolution. Figure 9 shows the temperature evolution at the location of leakage 3.

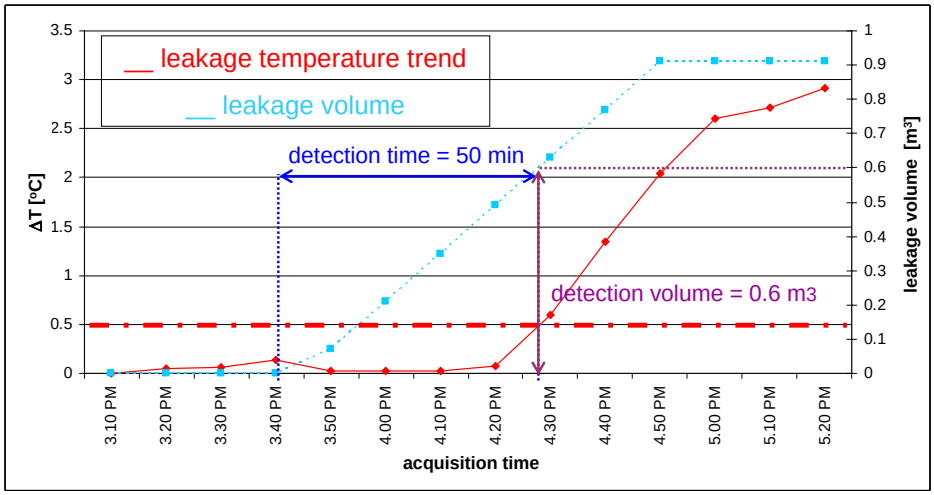

Figure 9. Temperature and leaked volume evolution at leak location 3.

In this case the leakage was started at 3:40 PM. The temperature started rising at 4:20 PM and reached the preset threshold level of 0.5°C at 4:30, 50 minutes after the leakage started. During those 50 minutes a total of 0.6 cubic meters of water have been released in the ground. The maximum temperature change was of the order of 3.5°C, while the injected water had a temperature of 20°C above the ground temperature. This experiment was one of those showing a relatively slow response because of the large lateral distance between the injection point and sensing cable. The following table resumes the results of all the performed tests:

Table 2. Summary of test results

Test	*Tap*	*Flow Rate [L/Min]*	*Water to ground temperature difference [°C]*	*Detection Time [min]*	*Leakage Volume [M^3]*
1	D1	10	20	1	0.005
2	D2	16	20	80	0.400
3	D3	14	20	50	0.600
4	D4	6	20	2	0.010
5	D4	13	4	75	0.800

In summary, this test simulates leakage along pipeline with a diameter between 12 and 32 inches with a flow rate between 300 and 3500 m3 per hour. Average flow rate of the leakage is 0.6 m^3 per hour, corresponding to a detected leakage of 0.1-0.01% of the transported volume. This is significantly better than any available volume balance method currently available. Detection time was between 1 and 80 minutes and the accuracy in leakage localization was better than 2 m. In test 5, performed in a different day, the temperature difference between fluid and ground was only 4°C, but the detection time remained in the order of one hour for a leakage of 0.01%.

The variability in the detection time and volume reflects the different local conditions and in particular:

- Permeability of the soil (type of soil)
- Compaction of the soil (presence of cracks and pockets)
- Proximity between the leakage and the sensor
- Temperature difference between fluid and ground

Figure 10. Gas leakage detection simulation test.

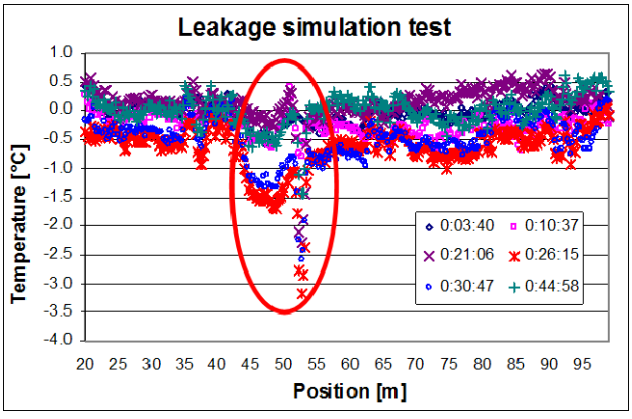

Figure 11. Temperature drop due to gas pressure release indicates the presence of a leakage.

3.2. Gas Leakage simulation

To evaluate the suitability of a distributed temperature sensing system for gas leakage detection, an experiment was performed on a real gas pipeline in Italy. A fiber optic temperature sensing cable was installed on the top of a 10" gas pipeline over a length of 500m. This installation was part of a larger test on measuring strain induced in the pipeline by a landslide. During the putting the sensors in place and burring of the pipe, an empty plastic tube was installed connecting the pipeline surface to the open air, 50 m far from the beginning of the instrumented zone. This tube was used to simulate a leakage of gas. In fact, carbon dioxide was inserted in the tube, cooling down the pipe and making

the thermal field surrounding the contact between the pipe and the tube similar to the conditions expected in case of a leakage. This process is presented in Figure 10. A total of 4 carbon dioxide tanks were discharged through the dummy pipe.
A reference measurement was performed before the tube was cooled down. After the carbon dioxide was inserted, the temperature measurements are performed every 2 to 10 minutes and compared with the reference measurement. The results of the test are presented in Figure 11. The test was successful and the point of simulated leakage was clearly observed in diagrams (encircled area in Figure 11). The recorded temperature drop was of 3.5°C.

3.3 Other applications

Besides the presented qualification tests, the described monitoring system have been applied in the following other pipeline applications:

- Brine pipeline of 55km in Germany, leakage detection
- Raw oil pipeline in Germany, temperature profile during pigging operations
- Monitoring of a 500m section of gas pipeline in Italy, evaluation of strain induced by landslide
- Ammonia pipeline of 3km in Italy, leakage detection
- Ammonia pipeline of 2km in Italy, leakage detection

The interested reader will find more details on these applications in the papers referenced in the bibliography.

4. Conclusions

The use of a distributed fiber optic monitoring system allows a continuous monitoring and management of pipelines, increasing their safety and allowing the pipeline operator to take informed decisions on the operations and maintenance of the pipe. The presented monitoring system and the qualification tests shown in this paper demonstrate how it is possible to detect and precisely localize leakages from oil and gas pipelines with unprecedented sensitivity.
Through the identification of temperature anomalies, it is possible to detect and localize leakages of small entity, which cannot be detected by conventional volumetric techniques. Furthermore, the ability to pinpoint the exact location of the leak allows an immediate reaction at the event location, minimizing downtime and ecological consequences.
Recent developments in distributed fiber sensing technology allow the monitoring of 60 km of pipeline from a single instrument and of up to 300 km with the use of optical amplifiers. To achieve the above-mentioned goals and take full advantage of the described sensing technology, it is however fundamental to select and appropriately install appropriate sensing cables, adapted to the specific sensing need. While it is generally easier to install sensing cables during the pipeline construction phases, it is sometimes possible to retrofit existing pipelines. In some cases it is even possible to use existing fiber optic telecommunication lines installed along a pipeline for temperature monitoring and leakage detection.

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