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DETECTION AND LOCALIZATION OF MICRO LEAKAGES IN MULTIPHASE PIPELINES USING DISTRIBUTED FIBER OPTIC SENSING

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Abstract

Gas and liquid pipelines often cross hazardous environmental areas, from the point of view of natural exposures such as landslides and earthquakes, and from the point of view of third party interferences 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, social and ecological consequences. Furthermore, the operational conditions of the pipeline itself can induce additional wearing or even damage due to corrosion, erosion and fatigue. The distributed and functional monitoring can significantly improve the pipeline management and safety. Providing regularly with parameters featuring the 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. The most interesting functional parameters are temperature distribution, leakage and third-party intrusion. Since the flowlines are usually tubular structures with kilometric lengths, functional 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 tool allowing monitoring over kilometric distances. Thus, using a limited 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 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 mass balance techniques. Fiber optic sensing systems are used to detect and localize leakages in liquid, 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.

This contribution presents recent testing results on controlled field trials. The tests demonstrate that it is possible to reliably detect oil leakages of the order of 10 liters to 1'000 liters per hour, corresponding to 0.01% to 0.1% of the pipeline flow. Tests were performed with small temperature differences between liquid and ground. The detection time was between 1 minute and 90 minutes. All simulated leakages were detected and localized to better than 2m accuracy. The paper describes the main parameters that affect the response time and detection volume, including the relative position of the leak to the sensing cable, temperature contrast and instrument performance.

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The second test presented in this paper was carried out in the framework of an Eni R&D project, Eni (Engineering Research & Development Department) and Tecnomare to develop and qualify a multi-phase leakage detection system based on DTS technology. Performances were verified during a phase of experimental activities in a custom-developed test plant, simulating operation of a buried pipeline and allowing generation of leakages with controlled characteristics. The test plant was characterized by significant peculiarities and improvements with respect to similar known experiences, in particular in terms of

- Use of a 14” real section of pipeline (with and without concrete coating) with 16 leakage points, distributed in 4 sections.
- Possibility to simulate liquid, gas and multiphase leakages.
- Reproduce the thermal field generated by the pipeline in the soil (temperature 35-65°C).
- Test over distances up to 25 km, simulating long pipelines.
- Optical DTS cables installed around the test pipe at different distances (0 to 40 cm) and radial position.

1. Introduction

Unlike electrical and point fiber optic sensors, distributed sensors [1, 2] 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 from 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.

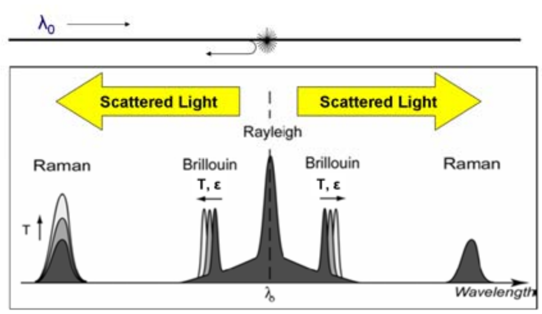

Fig.1. Light scattering in optical fiber.

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 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 an average strain and temperature readings over 1 meter. In this publication we would talk of a distributed sensing system with a measurement 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. Systems based on Brillouin scattering systems offer a temperature resolution of 0.1°C, a strain resolution of 20 $\mu\varepsilon$ and a measurement range of 30 km with a spatial resolution of 1 m [3].

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 and liquid 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 and liquid pipelines).
- In the case of multiphase pipelines a combination of the above can occur.

The above effects influence the ideal 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 from the leakage location. This is depicted in Figure 2.

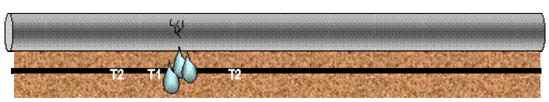

Fig.2. Detection of a liquid leak through a cable placed under the pipeline.

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 in such a situation is 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 3.

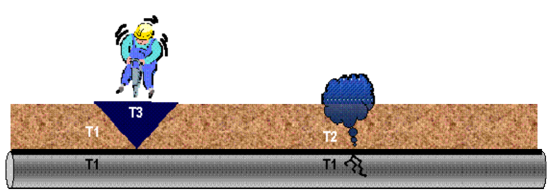

Fig.3. Detection of a gas leak through a cable placed above the pipeline.

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. Oil Micro Leakage Simulation

To simulate an oil micro leakage from a buried pipeline, a test has been performed at the premises of Praoil in Italy. 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 in respect to the sensing cable. Each tap was also instrumented with a volume meter to asses the leak volume. The temperature of the injected water could also be adjusted to simulate different operational conditions. Figure 4 illustrates the testing setup.

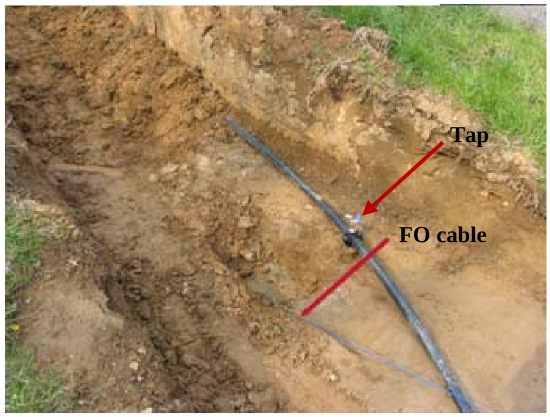

Fig.4. Leakage detection simulation arrangement. Several taps, with volume meters are used to generate controlled leaks.

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

Table 1. Test program

TIME	TAP	FLOW RATE [l/min]	TOTAL LEAK 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 5 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.

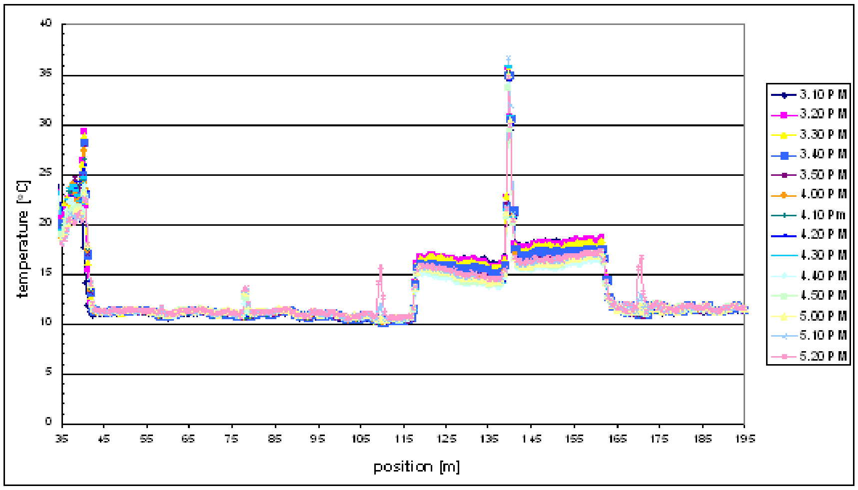

Fig.5. Raw temperature data for the leakage test.

The initial temperature variations, from the beginning of the cable to approximately 38m corresponding to a section of the sensing cable above ground, are due to different contact with the ground and sunshine conditions. From meter 38 to 117 the optical cable is buried in the ground and its temperature is much more constant, around 12°C. From meter 117 to 158 the optical 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 transform absolute information into relative information 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 6. All four micro leakages are now clearly visible. It has also been noticed that the first leakage was in the transition zone between buried and exposed section of the pipe and optical cable.

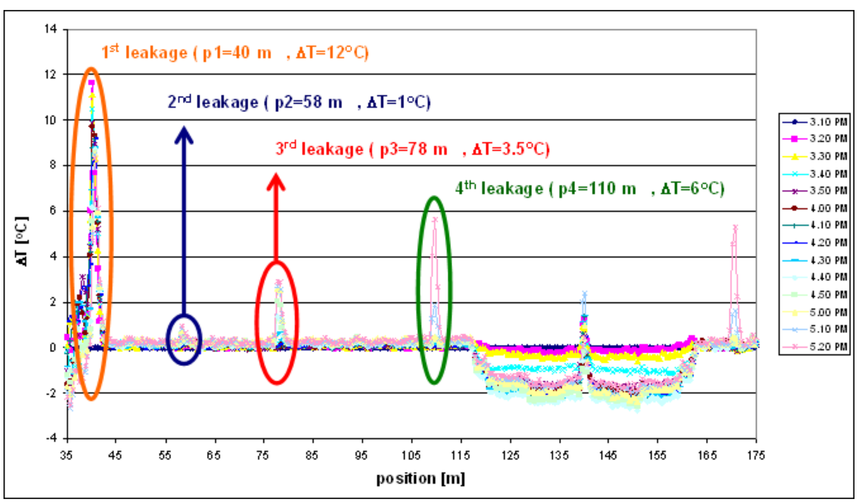

Fig.6. Relative temperature data for the leakage test.

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 7 shows the temperature evolution at the location of leakage 3.

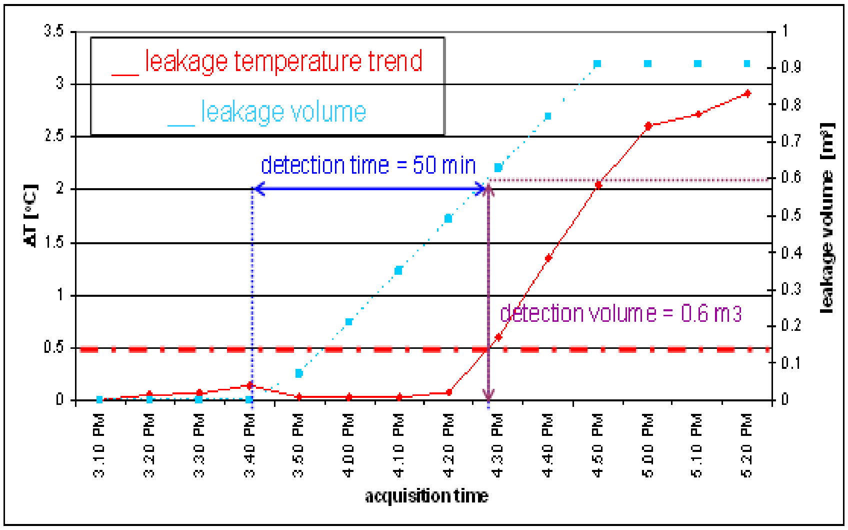

Fig.7. Temperature and leaked volume evolution at leak location 3.

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.

In a second testing day, one micro leakage was produced at position 110 m along the pipeline. The particularity of this test was the low ΔT of approximately 3°C between the injected water and the ground. Although these environmental conditions are unusual for oil pipeline it has been decided to perform this test to evaluate monitoring system capabilities. All the considerations that have been done for the first testing session are still valid. After acquisition and data processing we obtained the result shown in Figure 8 where the micro leakage is clearly visible.

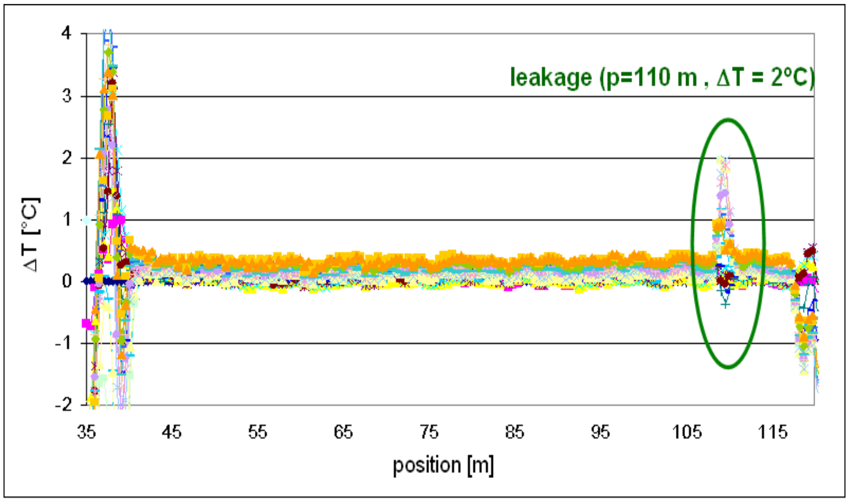

Fig.8. Relative temperature data for the leakage test.

In order to quantify the detection time and released volume we will now concentrate on the leak trend and observe the associated temperature evaluation. Figure 9 shows the temperature evaluation and leakage volume.

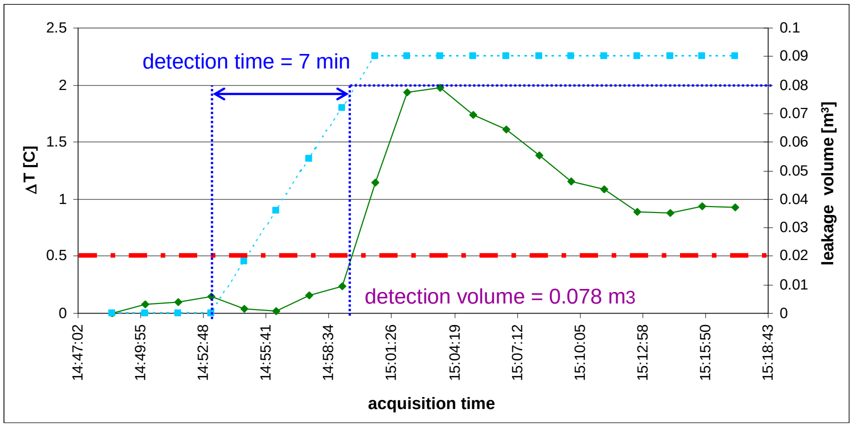

Fig.9. Temperature and leaked volume evolution at leak location D5, 2nd test with ΔT=3°C.

In this case the leakage was started at 14.52 PM, the temperature started rising at 14.57 PM and reached the preset threshold level of 0.5°C at 14.59 PM, 7 minutes after the leak started. During those 7 minutes a total of 0.078 cubic meters of water have been released in the ground. The temperature change was of the order of 2°C.

The following table resumes the results of all the performed tests, where ΔT is the water to ground temperature difference:

Table 2. Test results

TAP	FLOW RATE [l/min]	ΔT [°C]	DETECTION TIME [min]	LEAK DETECTION LACKAGE VOLUME [m^3]
D1	10	20	1	0.005
D2	16	20	80	0.400
D3	14	20	50	0.600
D4	6	20	2	0.010
D5	13	3	7	0.078

In summary, these tests used a small diameter pipe to simulate micro leakage along a larger pipeline with a typical flow rate between 300 and 3500 m3 per hour. Average flow rate of the leakage is 0.6 m3 per hour, corresponding to a detected leakage of 0.1 for a flow of 300 m3/h and of 0.01% for a flow of 3500 m3/h. 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 (difference between detected position and real position along the pipeline). In test 5, performed in a different day, the temperature difference between liquid and ground was only 3°C, but the detection time remained of only 7 minutes for a leakage of 0.078%.

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).
- Distance between the leakage and the sensor.
- Difference between temperature created by leakage and temperature of the ground.

4. Multiphase Leakage Simulation

In the framework of an Eni R&D project, Eni (Engineering Research & Development Department) and Tecnomare, with the support of Smartec, developed and qualified a multi-phase leakage detection system based on DTS technology during years 2007 and 2008. Performances were verified during a phase of experimental activities in a custom-developed test plant, simulating operation of a buried pipeline and allowing generation of leakages with controlled characteristics. The test plant was characterized by significant peculiarities and improvements with respect to similar known experiences, in particular in terms of

- Use of a 14” real section of pipeline (with and without concrete coating) with 16 leakage points, distributed in 4 sections.
- Possibility to simulate liquid, gas and multiphase leakages.
- Reproduce the thermal field generated by the pipeline in the soil (temperature 35-65°C).
- Test over distances up to 25 km, simulating long pipelines.
- Optical DTS cables installed around the test pipe at different distances (0 to 40 cm) and radial position.

Multiphase leakages were obtained mixing liquid and a gas flow generated by two different hydraulic circuits:

- Liquid leakage sub-circuit:
  - Leakage temperature: 35 - 65 °C.
  - Pressure: max 40 bar.
  - Flow rate: 0-20 l/min.
- Gas leakage sub-circuit:
  - Temperature: ambient temperature.
  - Pressure: max 40 bar.
  - Flow rate: 0-100 g/s.

Fig. 10. Test pipe before DTS cable installation.

Fig.11. DTS cables support cage placed over the test pipe.

Fig. 12. Liquid leakage circuit.

Fig. 13. Thermal map circuit.

Fig. 14. Gas leakage circuit.

Fig. 15. Nitrogen bottle packs.

Three FO cables were used as distributed sensors, for a total length of approximately 390 m. Long distance tests up to 25 km were carried out adding fiber optic spools between the DTS analyzer and the outdoor cable.

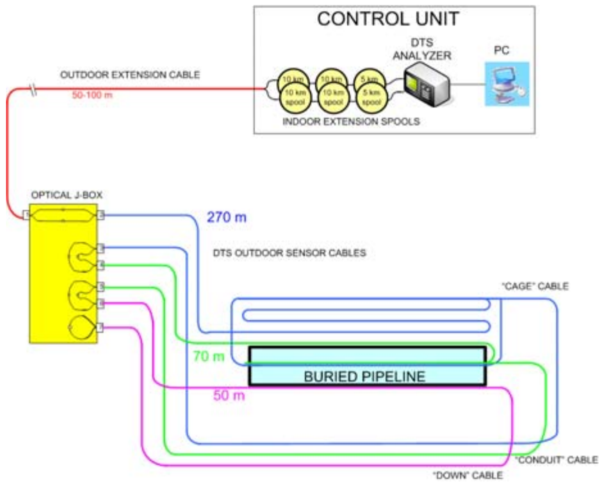

Fig.16. Test setup.

Results obtained in 22 multiphase leakage tests demonstrated capability of the fiber optic monitoring system to detect the temperature anomalies generated, also in the most critical conditions (very low flow rates). Significant examples are presented in the following.

4.1 Example 1

The following differential temperature plot (Fig.17.) represents a typical acquisition profile with a thermal map of 45°C and a multiphase leakage with liquid flow rate 2.5 liter/min and gas flow rate 5 g/s.

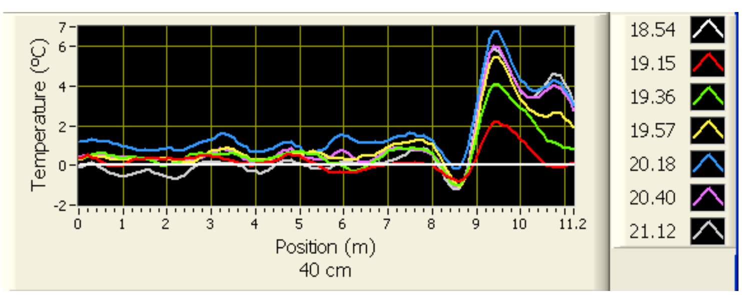

Fig.17.

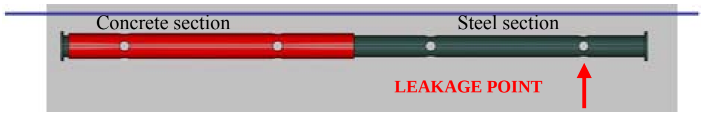

Fig.18. Leakage point.

The multiphase leakage creates a local heating around the pipeline. The heating effect due to the liquid prevails on the cooling due to the Joule-Thomson effect. This effect is clearly visible in correspondence of the leakage point.

4.2 Example 2

A similar test was carried out with additional 25 km of optical fiber (Fig.19). Test conditions: thermal map 55°C, multiphase leakage with liquid flow rate 10 liter/min and gas flow rate 4 g/s.

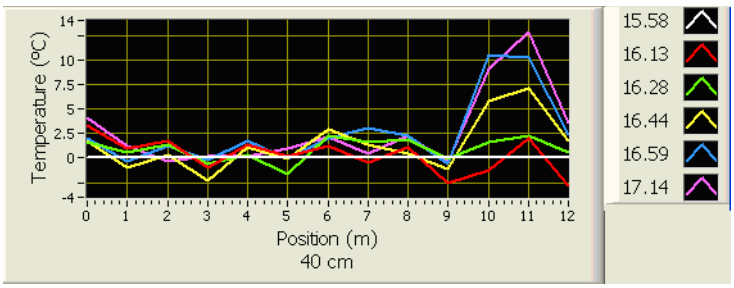

Fig.19.

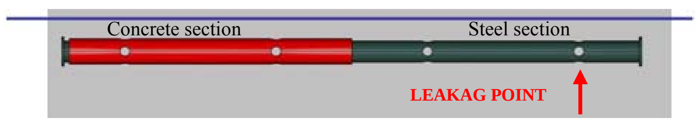

Fig.20. Leakage point.

This test demonstrates that the system correctly operates also at longer distances detecting temperature anomalies of several degrees.

4.3 Example 3

The following example refers to a leakage in the pipeline zone covered with concrete. Test conditions: thermal map 39°C, multiphase leakage with liquid flow rate 7.5 liter/min and gas flow rate 10 g/s. The following charts (Fig.21) illustrates how the leakage can be detected not only by the sensor positioned on the pipe surface (first chart), but also at distance of 10 and 20 cm.

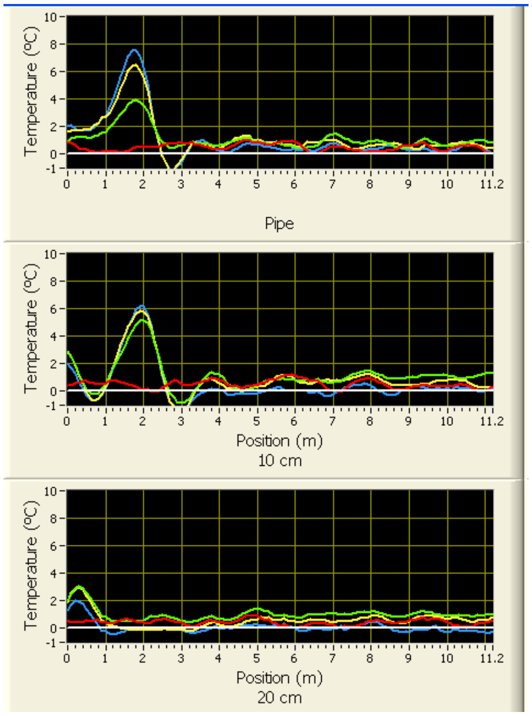

Fig.21.

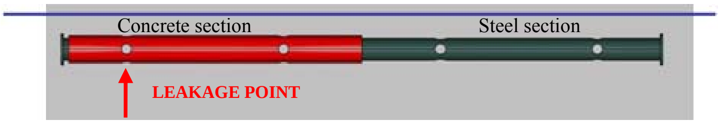

Fig.22. Leakage point.

Conclusion

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 immediate 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 micro leakages from oil and multiphase pipelines with unprecedented sensitivity.

Through the identification of temperature anomalies, it is possible to detect and localize small leakages, 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.

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