Offshore Pipeline Leak Detection System Concepts and Feasibility Study

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ABSTRACT

Detection of hypothetical leaks offshore and/or in the arctic requires particular attention due to the remoteness of resource locations and the sensitivity of the environmental conditions. A resulting and ongoing emphasis on asset integrity produces an interest in leak detection systems that have continual improvements in sensitivity and reliability.

In this paper, a discussion of offshore pipeline leak detection functional requirements is presented followed by an overview of the state-of-the-art systems, including a qualitative comparison and a discussion of technology gaps. A concept of integrated leak detection that employs complementary technologies is proposed. It is envisioned that the integrated leak detection concept will enhance leak detection reliability. The technologies considered in the concept are compensated volume balance computational pipeline monitoring (CPM) and distributed fiber optic (FO) sensors. Since the application of FO sensors to offshore pipelines is relatively new, an overview of application requirements and the feasibility of achieving such requirements are also presented.

KEY WORDS: Pipeline leak detection; Pipeline Integrity; Integrated leak detection; Distributed fiber optic; Feasibility study.

INTRODUCTION

The petroleum industry continues to move into challenging environments such as the ultra-deepwater offshore and the arctic as these resources start becoming economically viable for development. Producing hydrocarbons from these resources differs significantly from conventional offshore production in several aspects. In the case of the offshore arctic, conditions such as remoteness, limited access due to sheet ice cover for several months of the year, potential of ice gouging and wide operational temperature range (-50 °F – 50 °F) exist. In such conditions, it becomes more important than ever to be able to detect potential leaks. Thus, to ensure operational integrity in such environments, subsea leak detection systems that provide continuous monitoring capability and are highly sensitive and at the same time, experience fewer false alarms appear to be required.

This paper discusses the functional requirements for offshore and arctic pipeline leak detection followed by a brief overview of current leak detection systems. A high-level comparison of technologies is presented; technology gaps are identified and a combination of best available technologies is selected for the application under consideration. A novel concept to improve the performance of offshore pipeline leak detection systems is introduced that involves integration of complimentary leak detection principles to improve reliability. An algorithm to integrate multiple leak detection principles is presented. An example study that outlines the requirements posed on FO sensor cables and the feasibility of satisfying such requirements is also presented.

FUNCTIONAL REQUIREMENTS

Below is a summary of the principal functional requirements for leak detection system (LDS) for offshore and arctic applications.

Performance Requirements

Environment

The LDS should perform reliably at water depths ranging from 0 to 3000m. Wide installation and operational temperature ranges (0 – 30°C) should also be possible.

Coverage

The LDS should cover long pipeline lengths (~300km) for export pipeline applications. Shorter distances may be defined for other pipeline applications.

Spatial resolution

The spatial resolution is defined as the smallest distance span along the length of a pipeline over which a leak can be located. A LDS should locate leaks within a few (~5 - 10) meters along the line. Accurately locating a leak will allow remote intervention at site.

Reliability

The reliability of a leak detection system is a measure of its ability to render accurate decisions about the possible existence of a leak on the pipeline while operating within an established envelope of its performance. In other words, high reliability is to achieve a low
probability of having false alarms. A 95% confidence level is proposed for leak detection in sensitive environmental regions.

**Sensitivity**

Sensitivity is defined as the smallest detectable leak rate measured in volume per unit time and is a composite measure of the size of a leak that a system is capable of detecting and its response time (defined below). A leak detection system needs to be able to detect small leaks.

**Response time**

The response time is defined as the time elapsed between an actual event and the alarm trigger. An LDS should detect within a few minutes of occurrence.

**Production fluids**

The LDS should be capable of detecting leaks of water, crude oil, natural gas or any combination thereof. This requirement stems from the fact that in-field flowlines typically contain unprocessed well-stream contents that contain mixture of oil, water and natural gas. The specific fluid being transported should be defined at the outset.

Other performance requirements include the ability to quantify leak rate; the accuracy of predicting leak rate, volume and long design life.

**Installation Requirements**

External sensor instrumentation of an LDS should be designed such that it can be deployed offshore with a low risk of structural and functional damage.

**Operational Requirements**

An LDS should operate maintenance free. This requirement is based on lack of availability of infrastructure in remote areas. Also, the sensor power requirements in remote areas need to be minimized.

**STATE-OF-THE-ART LEAK DETECTION SYSTEMS**

Industry reports (ADEC report, Scott and Barrufet, 2003) provide technology overviews on pipeline LDSs. Here, only a brief overview of leak detection technologies is included (see Figure 1). At a high-level, LDSs can be classified into two categories: 1) continuous monitoring and 2) periodic inspection or survey type methods. Continuous monitoring technologies are further divided into short-range and long-range technologies and are applicable to subsea equipment and pipelines, respectively. Long-range monitoring of pipelines can be based on internal or external leak detection systems. Internal ones typically rely on detecting changes in pipeline flow conditions caused by a leak. External ones, on the other hand, detect effects of a leak on the pipeline surroundings. In what follows, current pipeline leak detection systems based on internal and external principles are briefly described.

**Computational Pipeline Monitoring (CPM)**

CPM is a wide-ranging term used to describe many computer-based leak detection systems. It uses pipeline flow, temperature and/or pressure measurements, governing models and alarm evaluation for leak detection and confirmation. The governing models can be based on mass balance, volume balance, pressure measurements, transient fluid flow models, acoustic (also termed as negative pressure rarefaction) and/or statistical analysis of historical pipeline events. More information on CPM is given in Whaley et al. 1991. CPM is the most commonly utilized and mature technology for pipeline leak detection and has been used in both onshore and offshore applications and the governing models have been tested extensively. The main limitations of CPM include lower sensitivity due to instrumentation performance and false positive alarms in transient pipeline conditions.

**Vapor Monitoring**

This system utilizes an external small flow tube along the pipeline. The tube structure is permeable and allows hydrocarbons coming into contact to get absorbed. A gas of known composition is constantly pumped through the tube. A mass spectrometer device is used to detect the presence of any hydrocarbons at the end of the tube. This technology is claimed to have high sensitivity but can take multiple hours for leak detection (Knoblach and Bryce 2011). This is a relatively new technology and has been mainly used onshore with a few offshore applications.

**Distributed Fiber Optic (FO) Sensors**

Although fiber optic is not a new technology, the use of fiber optic cables as strain, vibration and leak detection systems along pipelines is currently an emerging and promising application of this technology. This is external type of leak detection system. Pulses of laser light are sent into a FO cable laid along the length of the pipeline. The light is partially backscattered by the cable material throughout the cable length generating scattered components. This backscattering process is influenced by the cable physical properties, which are in turn dependent on the ambient temperature changes and acoustic vibrations that may be caused by pipeline leaks. Therefore, by analyzing the characteristics of the backscattered light, information about the pipeline leaks along the cable may be obtained. This technology is claimed to have high sensitivity and can locate events along the length of a pipeline within few meters of the source. Similar to vapor sensing, FO sensor technology is relatively new and has been mainly used onshore with a few offshore applications.

**Passive and Active Acoustic Sensors**

Passive acoustic leak detection involves sensing the pressure wave or sound generated by a leak. This is an external type of system and could be used for periodic inspection or determining leak location after a leak alarm has been generated by a method such as CPM. These sensors can be mounted on ROV or towed fish. The pressure difference created by the leak is the most important parameter in detection. The instrumentation signals are filtered using advanced signal processing software. The signal is characteristic of leak flow rate, pressure drop, type of fluid. Passive acoustic leak detection systems are robust, simple, low-cost, and are not affected by sea turbidity or currents.

Active acoustic leak detection, on the other hand, involves use of sonar technology. Sound pulses sent towards targets determine the presence of leak through impedance difference with respect to water. Active acoustic systems could be used to detect small leaks where a pressure drop due to leak does not generate significant signal. The main limitation of these systems is inoperability that can result from the acoustic shadow of adjacent structures. Also they are not suitable for continuous monitoring of pipelines due to the long distances that need to be monitored.
SYSTEM COMPARISON AND TECHNOLOGY GAPS

A qualitative study was performed to understand the performance of the above-mentioned systems in the light of the functional requirements outlined above. The outcome of this study is provided in Table 1 where each LDS is rated on a scale between 1—5, 5 being the most suitable. It is emphasized that this study did not involve performance testing of any specific technology. This study indicated the following main technology gaps.

1. Reported experience (PRCI Report, 2007) identifies many of the mass or volume balance CPM systems as susceptible to false alarms. For pipelines operated in remote areas, it is essential that the number of false alarms generated be minimized without compromising the sensor sensitivity. Moreover, uncertainties in hydraulic calculations during slack and multi-phase pipeline flow conditions can pose a further challenge to operation of CPM systems.

2. The successful application of fiber optic cables and vapor sensing tubes for offshore pipeline leak detection is yet to be demonstrated. Although the external leak detection technologies have potential for application in offshore conditions, no independent data verifying their capabilities are available. Depending on the principle of operation of a system, performance qualification protocols should be developed, in particular for underwater applications.

3. Robust installation procedures must be developed to protect external sensors such as fiber optic cables to prevent mechanical damage during offshore installation. This would involve design and development of auxiliary equipment for offshore sensor installation.

4. For long distance pipeline monitoring applications, the development of systems for power supply and reliable communication are needed to ensure continued operation of the monitoring sensors.

LEAK DETECTION SYSTEM SELECTION

Based on the understanding of functional requirements and limitations of current pipeline leak detection systems, it is apparent a concept of simultaneous use of complementary technologies could enhance overall performance. One such concept involves combining compensated volume balance or statistical CPM with distributed FO sensors to take advantage of their complementary operational characteristics. The development of the integrated leak detection concept requires a methodology for combining such systems. As mentioned before, CPM systems have been applied offshore, are mature and do not require much development work. But, distributed FO systems have had limited offshore use and require confirmation of feasibility. In what follows, aspects of an integrated leak detection and FO feasibility study are discussed.

INTEGRATED LEAK DETECTION SYSTEM

An integrated leak detection concept involving CPM and distributed fiber optic sensors is shown in Fig. 2. It consists of one or more fiber optic cables along a subsea pipeline in conjunction with intermittent pressure and flow meters. At a higher level, the two technologies work independent of each other to determine the presence of a leak.

At the software level, the outputs from the two methods can be combined to improve the reliability of leak detection. An example flow chart for such software-level computations is shown in Fig 3. The example leak detection will work in the following way:

1. Detect and locate a leak using a distributed fiber optic sensor based technology. It is expected that FO sensors will, in general, be able to detect smaller leaks before CPM responds.

2. Confirm and predict leak volume using compensated volume balance technology. To confirm the presence of small leaks, CPM technology sensitivity may be adjusted to take into account the flow variations in the pipeline.

3. Combine outputs from both techniques to improve reliability i.e. eliminate false alarms.

It is noted that the temperature differentials (ΔT) comparison in Fig. 3 needs to be accompanied by a confidence level that depends on knowledge of pipeline flow conditions and the surrounding environment. The performance of such an integrated leak detection system will depend on the ability to provide a power source and communication interface to intermittent flow/pressure transducers in remote areas. An integrated cable structure can be designed to provide power, sensing and communication interface.

FO CABLE OFFSHORE APPLICATION FEASIBILITY

As mentioned before, the use of distributed FO sensor technology for pipeline leak detection is still new and has not been proven for offshore pipelines. This requires that an understanding of the requirements on FO sensor cables for offshore leak detection application be developed in order to demonstrate technical feasibility. A broad perspective of the different aspects that must be addressed to ultimately qualify distributed fiber optic sensors to offshore applications is illustrated in Figure 4. In what follows, we briefly discuss, leak characterization, fiber optic sensor performance, installation and operational requirements and comment on feasibility of achieving such requirements. A joint industry project (JIP) has been formed to address such aspects of sensor qualification and currently the JIP is working on first phase to understand sensor performance. The next phases of the JIP are planned to address leak characterization and fiber optic sensor installation and operational aspects.

Leak Characterization

To understand if a given FO sensor system will detect the presence of a leak it is important to study the temperature profile that might arise around a hypothetical subsea pipeline leak. Understanding of leak temperature profile also leak helps to identify location and number of fiber optic cable sensors. To that end, coupled CFD-heat transfer simulations of a subsea pipeline with small leaks were conducted.

The commercial CFD code Fluent (Fluent 2010) has been used for the CFD analysis. A conjugate heat transfer model (solid conduction and
fluid convection) has been developed to evaluate the temperature profiles in the pipe walls and the surrounding fluid.

Depending on the hypothetical leak location around the pipe and its size, pipeline fluid type, and the surrounding water current velocity and direction, leakage would cause variations in temperature profile along the pipe and in the circumferential direction. The fluid flow and temperature profiles around a hypothetical leak from a CFD simulation are shown in Figure 5. This example simulates crude oil leaking into sea water through a simulated circumferential crack at the 10 O’clock position in a pipeline. It is observed that depending on water current direction, the leaked fluid will contact the pipe surface only at limited positions in a pipeline. It is observed that variations in temperature profile along the pipeline at different circumferential locations. As can be seen in the figure, the highest temperature change (approximately 18ºF) due to the leak is at the crack location (10 O’clock position). A smaller temperature change (~2ºF) is observed at other locations such as the 2 O’clock position. This indicates that multiple (2 or 3 in this case) FO sensor cables may be required at different circumferential position for effective leak detection using fiber optic sensors. It is noted that these CFD results are not validated against any experimental data and further work is needed. However, the results can be helpful to understand temperature profile around a leak and to locate FO sensor cables.

**FO Sensor Performance**

The performance characteristics (sensitivity, accuracy, spatial resolution and distance range) of temperature based fiber optic sensors have been studied in the literature (Nikles, 2009). The performance of distributed FO sensors is a function of several parameters including the fiber length, optical attenuation, data acquisition time and pulse width of the laser being shined into the optical fiber. Based on literature, the temperature gradient measurement sensitivity of a typical sensor can range between 0.5ºC - 3ºC, depending on location along the length of the sensor cable.

Based on the leak characterization study and an understanding of performance of fiber optic sensors, it is expected that distributed fiber optic sensors appear to be a promising technology for detection of leak events especially if the sensor cable is close to a subsea pipeline leak.

**Sensor Installation and Operations**

**FO sensor installation**

The requirements for installing FO sensor cable as part of offshore pipeline installation also need to be considered in order to understand the feasibility of this technology. Proper FO cable installation needs to address the following main aspects:

- Damage avoidance strategies and protection for FO cables (crushing, abrasion)
- Techniques to attach FO cable to the pipeline
- Number-spacing of FO cables
- Type and location of tensioner and stinger support roller boxes
- Mechanical and space requirements for FO cable attachment station on offshore pipeline installation vessels

- Weather considerations for installation in deepwater and arctic regions

To avoid damage, the roller box design on stingers could be modified while steel armoring wires can be used in the cable cross-section to provide sufficient crush and abrasion resistance during installation conditions. Continuous wraps and/or polymer straps can be used to attach the cable system to the pipeline. Under certain conditions, continuous wraps could improve detection by carrying the hypothetically leaked fluid to the sensor location. Figure 6 shows a possible configuration of multiple FO cables attached to a pipeline. It is envisioned that FO cable attachment station will be located just prior to the stinger on the installation vessel. Proper planning for weather conditions including temporary cable abandonment procedures may be performed during inclement weather.

**FO sensor operations**

In what follows, several operational requirements posed on FO sensor cable are considered and the feasibility of satisfying such requirements is briefly discussed.

For offshore and arctic applications, the FO sensor cable will be subjected to a range of operating temperatures (0ºC – 45ºC). Standard telecommunication grade cables that can be used for sensing have wider operational temperature ranges (-30ºC – 60ºC) and are expected to satisfy the temperature requirement. Further, in the case of deepwater offshore applications, FO sensor cables will be subjected to external hydrostatic pressure, which is again feasible based on cable designs used in telecommunication industry. Because of the attenuation of signal along an optical fiber, repeaters are required at approximately 40km interval for amplifying the optical signal. But these repeaters require power. It is envisioned that the power transmission/optimization concepts from standard telecommunication industry can be utilized. During the operation of a distributed FO sensor, a reasonable alarm threshold must be set and real-time data processing is required. Although such data processing software have already been developed by sensor vendors and it still may require further development and qualification. Another challenge presented by the offshore environment is potential damage to the sensor cable due to submarine activities such as anchor dragging. Repair of cables subsea seems infeasible at this time. It is anticipated that the presence of a steel pipeline next to sensor cable will reduce this risk to some degree. One way to mitigate this risk is to provide sufficient sensor cable redundancy along the pipeline.

**CONCLUSIONS**

- Functional requirements for the selection of a leak detection system for offshore pipelines have been proposed.
- A brief summary and qualitative comparison of current pipeline leak detection technologies has been presented. Distributed FO sensors appear to be the best available technology for offshore applications.
- Following a technology gap study, an integrated leak detection concept that combines complimentary leak detection technologies has been proposed to enhance leak detection reliability.
The three main aspects for the qualification of a FO system for offshore applications require understanding of leak characterization, sensor performance, and installation and operations. The requirements posed on FO sensors considering these aspects have been outlined and the feasibility of achieving such requirements was discussed.

A coupled CFD-heat transfer study indicates enough temperature change might be created by a hypothetical subsea leak for FO leak detection to occur, but the sensor cable needs to be close to the leak for effective leak detection. This finding suggests that multiple sensor cables will be required.

Installation of FO sensors on offshore and arctic pipelines will require a robust cable design, cable attachment method and weather dependent planning.

Based on experience from the telecommunication industry, FO sensor cables are expected to survive offshore environment temperature and pressure requirements. Concepts from the telecommunication industry may be applied to provide power to intermittent repeater stations for long distance sensing applications.

REFERENCES


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Figure 1: Leak detection principles overview.

- **Continuous monitoring**: Permanently installed systems
- **Inspection/Survey**: Sensors on mobile units, ROV or AUV, Pigs

**Short-range monitoring**
- Subsea Equipment

**Long-range monitoring**
- **Internal Detection**: Mass/flow balance, Pressure drop, Acoustic
- **External Detection**: Vapor monitoring, Fiber-optic cables

Figure 2: Integrated leak detection concept showing required hardware installation on a subsea pipeline. It is noted that in this depiction, the distance between pressure or flow sensors is not indicative of what an integrated leak detection concept will require.
Figure 3: Algorithm for integration of outputs from complementary leak detection technologies to improve reliability of leak alarm.

Figure 4: Feasibility study elements of distributed fiber optic sensors for offshore pipeline leak detection application.
Figure 5 (a) Example fluid flow from a hypothetical numerically simulated subsea leak (longitudinal crack at 10’O clock position); (b) Corresponding longitudinal temperature profile on pipe surface.

Figure 6: Example locations of multiple FO sensor cables on a pipeline.