ABSTRACT

This paper will demonstrate that with limited instruments at the terminals and platforms only, it is feasible to monitor the integrity of offshore pipelines effectively. Some examples of applications will be shown, including both crude oil and natural gas pipelines.

The statistical volume balance technology based on flow and pressure measurements at the inlets and outlets only provides the detection and location of leaks. The paper describes the performance of these leak detection systems for incidents ranging from small leaks to pipeline rupture.

To help operators run pipelines safely and cost effectively, real-time transient models are used to calculate the flow, pressure, temperature, density and other fluid properties along the pipeline. Instead of using measured flow and pressure, the operators rely on these calculated values to take operational decisions. The combination of hydraulic modelling and statistical leak detection provides the operators with the information and confidence in the integrity of their pipelines. In the event of any incident the operators can take actions quickly and correctly to minimize the consequences.

INTRODUCTION

The safe and reliable operation of offshore pipelines is critical to protecting the environment and viability of commercial entities. Recent experience shows that the consequence of a single incident offshore can rise to billions of dollars in financial loss and unlimited liability and damage to a company. It is even more technically and economically challenging to have fully instrumented and protected facilities offshore than onshore.

Although leak detection and integrity management have brought much attention to cross country pipelines [1], [2], [3], [4], [7], [8], [10], the application to offshore pipelines is relatively limited [5], [6]. However most of the leak detection technologies described in API 1130 [9] are feasible for offshore pipelines.

This paper will address the application of the statistical volume balance leak detection and on line hydraulic simulation to the offshore oil and gas pipelines.

The statistical volume balance system is one of the statistical analysis methods referred to in API 1130 [1], [2], [6], [7]. It uses the corrected volume balance in conjunction with sophisticated statistical techniques to provide reliable leak detection and leak location. It has been successfully applied to more than 800 pipelines world-wide with various fluids, pipeline dimensions and operating transients.

The engine to this statistical volume balance technology is the Sequential Probability Ratio Test (SPRT): a hypothesis testing method used to decide between a leak and no-leak scenario ([11], [2], [7]). The data used for the sequential probability ratio test is the inventory compensated volume balance. The SPRT calculates the ratio of the probability of a leak over the probability of no-leak and decides if the corrected volume balance has increased with a predetermined probability e.g. 99%.

The hydraulic simulation software provides the real time transient model for single phase gas or liquid pipelines. It can simulate pipeline networks in steady state and fully transient state. It solves the coupled balance equations for mass, momentum, and energy in the fluid and if the user requires, it can also simulate the thermal energy exchange with the ambient surrounding the pipe.

The simulation software computes the flow (standard, actual, and mass), pressure, and temperature at every point in the pipeline. It calculates quantities derived from the equation of state and other fluid property models: density, viscosity (kinematic and dynamic), speed of sound, heat capacities, heating values, etc. It reports a detailed description of the flow in profile form for each pipe: gas velocity, Reynolds number, friction factor, super-compressibility. It also provides as standard calculations line pack and other tools to support line pack management.
We have deployed the statistical volume balance and hydraulic simulation technology on pipelines with diameter ranges from 0.5" to 80" and length from 2 KM (1.2 mile) to 2100 KM (1305 mile). The pipelines are located in 55 different countries both offshore and onshore. This paper addresses the application to the following offshore pipelines:

- Crude oil and natural gas pipelines in Sakhalin Island, Russia
- Crude oil pipelines in Gulf of Mexico, USA
- Natural gas pipelines in Philippines and
- Natural gas pipelines in the North Sea, Norway.

**DESCRIPTION OF THE SIMULATION SOFTWARE**

The simulation software uses a highly stable fully implicit finite difference method to solve the pipeline equations [21]. This method uses an automatically adaptive time step and an automatically adaptive spatial mesh that are unique in the industry. The adaptive time and space meshes mean that the users need not worry about configuring details of the numerical solver - they are all handled in a completely automated manner. All the user needs to do is specify the desired accuracy, and it will configure itself to model the pipeline in detail only when and where necessary, while using less detail and adequately longer time steps in regions of steady state linear behaviour.

In addition to hydraulic simulations, the simulation software has a control system emulator that simulates PID (Proportional, Integral and Derivative) and logic controls. The user creates and edits Control Diagrams via drag and drop tools to implement these controls. The inclusion of control system simulations makes operator training simulators or Trainers much more authentic.

The equations used to derive the calculations in the thermal and hydraulic model are described below.

**The conservation of mass:**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial x} = 0
\]

**The conservation of momentum:**

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho v^2)}{\partial x} + F = 0
\]

**The conservation of energy:**

\[
\rho c_v \left( \frac{dT}{dt} - \mu \frac{dP}{dt} \right) + \rho v c_v \left( \frac{\partial T}{\partial x} - \mu \frac{\partial P}{\partial x} \right) + \rho g \frac{\partial z}{\partial x} + 4H \frac{T - T_e}{OD} = 0
\]

Where

<table>
<thead>
<tr>
<th>P</th>
<th>(Absolute) Pressure of the fluid</th>
</tr>
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<tbody>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>z</td>
<td>Elevation of a point in the pipe.</td>
</tr>
<tr>
<td>\mu</td>
<td>The (absolute) dynamic viscosity of the fluid (Reynolds number)</td>
</tr>
<tr>
<td></td>
<td>The Joule Thompson Coefficient of the gas (Thermal equations)</td>
</tr>
<tr>
<td>T</td>
<td>(Absolute) Temperature of the fluid</td>
</tr>
<tr>
<td>cp</td>
<td>Specific heat capacity at constant pressure of the fluid</td>
</tr>
<tr>
<td>H</td>
<td>Heat Loss coefficient to the ground</td>
</tr>
<tr>
<td>Tg</td>
<td>Ground Temperature</td>
</tr>
<tr>
<td>OD</td>
<td>Outer diameter of the pipe</td>
</tr>
<tr>
<td>F</td>
<td>Total force acting on the volume</td>
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</table>

The above partial differential equations are solved simultaneously with the equations describing device behaviour (compressor or pump maps, valve equations, heater and cooler set points, choked or free flow, equations for simulated leaks, resistance equations, etc.). For accurate and robust online simulation, the Maximum Likelihood State Estimator is used to utilize all of the available measurement data while weighting towards the meters which are the most accurate [20].

**APPLICATION EXAMPLES**

The following sections describe four offshore application examples in different parts of the world.

**Sakhalin, Russia**

The pipelines in Sakhalin have been constructed by two major projects: Sakhalin 1 and Sakhalin 2. These projects involved the construction of offshore and onshore pipelines as part of the overall development of the offshore oil and gas fields in the Sea of Okhotsk, north of Japan.

The Sakhalin projects were technically challenging as they were located in a hostile subarctic environment, and covered a vast area in a region with almost no existing infrastructure. The developers had to tackle environmental, ecological and social issues.

Sakhalin 1: The crude oil pipeline starts from Chayvo OPF facility in Sakhalin Island and runs 202 km (126 mile) to Dekastri Marine terminal on the Russian mainland. It crosses the Tatar Strait under water (Figure 1). From Dekastri Marine terminal, an offshore pipeline measuring 48" and 17 km (11 mile) long loads tankers at SPM intermittently. The gas pipeline runs from Chayvo OPF to Boatasyno station and it is 24" in diameter and 17 km (11 mile) in length.
Sakhalin 2 includes more than 1600 km (994 mile) onshore and 300 km (186 mile) offshore pipelines with diameters ranging between 14” and 48” [12].

Two 800-kilometer (497 mile) pipelines, which bring oil and gas from the fields in the north of the island to the ice-free export terminal in the south, traverse mountainous terrain in an earthquake zone and cross more than 1,000 watercourses, many of which are ecologically sensitive.

The Sakhalin 2 pipelines are located in three main groups between the offshore platforms, situated to the northeast of Sakhalin Island in water depths of up to 50 m (164 feet), and an onshore processing plant situated near the coast in the northeast of the island and an LNG plant in the south of the island. The two northern groups of the pipelines transport oil, gas, and condensate in single and multi-phase states from three offshore production platforms to the onshore processing plant, where the well streams are separated and treated.

There is also a pipeline from the onshore processing plant to Luskskoye-A, the most southerly offshore platform of the fields, transporting regenerated mono-ethylene glycol (MEG) back to the platform for re-use in the multi-phase pipeline.

The third group of pipelines transports gas and oil from the onshore processing plant to the LNG plant and the oil export terminal in the south of the island. Another crude oil loading pipeline runs from the oil terminal to a single-buoy mooring of the tanker-loading unit offshore.

To meet the stringent environmental requirements, pipeline leak detection and pig tracking systems were specified from the start of the projects. This included both offshore and onshore pipelines. The statistical volume balance system was implemented on Sakhalin 1 in 2006 and Sakhalin 2 in 2008. For each of the pipelines, the following metering values are available from the DCS/SCADA system:
Flow, pressure and temperature at the inlet and outlet
Pressure and temperature at block valves for the onshore sections
Valve status at the inlet and outlet
Pump/compressor on/off status
Pig launcher and receiver signals

Since the offshore pipeline section is part of the pipeline from the offshore platforms to the onshore processing facility or marine terminal, the integrity monitoring covers the entire pipeline. Over the past 10 years the pipeline operating conditions have been changing continuously due to ever increasing production capacity, both the leak detection and pig tracking systems have continued to work effectively.

In addition to seven oil and gas pipelines, the statistical volume balance leak detection system has also been applied to the following pipelines:

- A 21 km (13 mile) long MEG pipeline
- Two 21 km (13 mile) long multi-phase loading pipelines.

The multi-phase pipelines are mostly offshore and they transport gas, a small amount of condensate and MEG. Operations first separate the liquid and gas at each end of these pipelines, before single phase flow meters measure each stream. With such flow and pressure measurements at the inlet and outlet, the statistical leak detection system works effectively without the need of a multi-phase model.

The pipeline operator has tested the performance of the leak detection systems both by controlled product releases and unusual pipeline operations. For example, the system correctly issued 18 leak alarms in 2015 when the operator opened the riser valves, depressurising one of the multi-phase pipelines.

Each of the ten leak detection systems has been optimized based on the instruments available and operating conditions. The data sample intervals are 10 seconds for nine pipelines and 5 seconds for one short gas pipeline. Some examples of the leak detection system performance are listed below:

1. For the long oil pipelines, the LDS detects a 1% leak in 2 hours and a 5% leak in 15 minutes.
2. For the long gas pipelines, the LDS detects a 2% leak in 2 hours and 5% leak in 40 minutes.
3. For the multi-phase pipelines, the LDS detects a 1% leak in 20 minutes and 5% leak in 5 minutes.

As integrity monitoring has been a key part of running the pipelines in Sakhalin from the start of commissioning, the pipeline operators have become dependent on the leak detection and pig tracking systems. The pipeline owner would not consider operating the pipelines without these systems.

Gulf of Mexico, USA

There are many pipelines in the Gulf of Mexico. This paper addresses the application of the statistical volume balance system on two crude oil pipeline systems:

- Caesar Pipeline [13], [14], [15] and
- Cameron Highway Oil Pipeline (CHOP) [16], [17]

Figure 3 shows a map of these two pipelines [17].

The Caesar Oil Pipeline System in the southern Green Canyon Area includes a trunkline from the Holstein spur to a shallow-water platform at Ship Shoal Block 332 (SS332) in 430ft (131 m) of water. A lateral pipeline from the Mad Dog spur ties into the Caesar pipeline and another lateral pipeline from the Atlantis semi-submersible facility ties into the Mad Dog lateral. The pipelines are about 115 miles (185 KM) long, including laterals, and are the first of their size to be laid in water depths greater than 5,000 feet (1524 m) in the Gulf of Mexico. From SS332 production it feeds into Cameron Highway (CHOPS).

The Cameron Highway System is a 380-mile (612 KM), 24 and 30-inch oil pipeline which extends along the Outer Continental Shelf ("OCS") of the Gulf of Mexico and delivers crude oil from major deepwater oil fields to markets on the Texas Gulf Coast [16], [17]. The system originates at the Ship Shoal 332 A/B Hub as a 30" diameter pipeline, extends across the GB 72 platform and then splits into two 24" diameter pipelines at the High Island A5-C platform. One 24" leg terminates in Texas City, Texas, while the second terminates in Port Arthur, Texas.
logics, and numerous operating scenarios for both normal and abnormal pipeline operations [18]. The operators were running the pipelines and experiencing various emergency scenarios within the controlled environment by the use of the Training Simulator, months before the pipelines were commissioned. This gave them confidence in operating the pipelines and insight to how the pipeline and control system behaved.

The leak detection system performance of these two pipeline systems are slightly different. In fact the CHOP system consists of five individual leak detection units with each optimized for that pipeline segment. Typically

- a 1% leak is detected in 60 minutes and
- a 5% leak is detected in 15 minutes.

The statistical volume balance systems have been running on both Caesar and CHOP systems satisfactorily since 2004. Minimum or no false alarm has been experienced over the past 12 years.

Malampaya Pipeline, Philippines

Malampaya oil platform is the only operational oil platform in the Philippines. It extracts natural gas from the Malampaya Field, located 80 kilometres (50 mi) west of northern Palawan. The 504 km (313-mile) underwater pipeline transports the gas from the field to Batangas City. An onshore gas plant receives the gas for further processing, then sends it to three power plants [19] through the onshore pipelines.

One of the main challenges in operating a long subsea pipeline such as Malampaya Export Pipeline is the lack of process measurements available. While flow, pressure and temperature are metered on the offshore platform, the only other measurement point is at the onshore gas plant in Batangas. We implemented a real time transient model (RTTM) to provide the necessary information to the pipeline operators, as well as the statistical volume balance leak detection system.

The main functions of the RTTM system include:

- Calculations of flow, pressure and temperature along the whole pipeline, the calculated values serve as virtual metering data
- Look-ahead modelling to predict future pipeline conditions if certain operating scenarios occur

The real time model is tuned to the measured flow and pressure at the inlet and outlet of the pipeline. It is important that the model is accurate so that the operators can rely on the calculated values for decision making. Figure 5 shows a trend where the calculated flow and pressure are compared with the measured data over a period of 60 hours.

As shown in Figure 5, although the pipeline is packing and unpacking continuously, and outlet flow changes by more than 40% regularly, there is a good match between calculated and metered flow and pressure. This gives the operators confidence in the calculated values where no meters are available.

To help understand and plan emergency responses in the event of a real pipeline leak, the simulation model is also used offline to generate flow and pressure responses when leaks of different hole sizes occur at different locations. This includes rupture simulations too.

Figure 6 shows an example of how the statistical volume balance system detects a simulated 1” hole within 2 hours.

Since it is not feasible to flare gas anywhere between the Platform and onshore, the simulation software has proven invaluable in analyzing the performance of the leak detection system. One of the major benefits of the leak simulation studies is the identification of possible improvement in the leak location estimates. Since the first implementation of the simulation and leak detection system on site in 2001, two major upgrades of the systems have been provided. The current leak detection system is able to locate all the 1” holes within 4.3% of the pipeline length. This makes it much more effective for the pipeline operators to take correct actions in the event of a real pipeline leak.

Figure 4 Malampaya Offshore Gas Pipeline Route [19]
Figure 5 Comparison between measured and calculated values over a 60 hour period for the 504 km (313-mile) long offshore gas pipeline (Plot 1 – Inlet flow: calculated in red, logged in purple, Plot 2 – Outlet flow: calculated in orange and black, logged in grey and brown, Plot 3 – Inlet pressure: calculated in brown, logged in blue; Plot 4 – Outlet pressure: calculated in green, logged in yellow).

Figure 6 Detection of a simulated 1” leak for the 504 km (313-mile) long offshore gas pipeline (The top chart shows the inlet flow in purple and outlet flow in brown, together with the statistical responses lambdas 1 to 3. The bottom chart shows the KL leak location estimate in green and leak size estimate in orange, the speed of sound leak location in red).
Figure 7 Schematic of the Gassco operated subsea gas pipeline network [20]

Figure 8 Model results Using Flow Nomination Data (greyed area shows the look-ahead data, white area shows historical data)
Gassco, Norway

Gassco operates the integrated system for transporting gas from the Norwegian continental shelf to other European countries. It delivered a total volume of 108.4 BSCM (billion standard cubic meters) of gas to receiving terminals in 2015. This is all done through a subsea network of 7,800 KM (4,847 mile) pipelines. Figure 7 shows the pipelines in the North Sea.

As shown in Figure 7, these subsea pipelines range between 300 km (190 miles) and 900 km (560 miles) in length, with diameters up to 1.118 meter (44 inch). Since measurements are only available at the pipeline inlets and outlets above sea level, the online application of the pipeline simulation models helps pipeline operators run the complex pipeline networks safely and reliably.

The online simulation tool consists of 17 separate pipeline models that monitor the gas pipeline network as part of the Pipeline Management System (PMS). State estimation, using the Maximum Likelihood State Estimator which utilizes all of the available measurement data for flows and pressures provides an up to date calculation of the hydraulic and compositional properties of the gas in the pipeline network.

Tuning algorithms for the pipeline efficiency and flow meter offset enhance the online simulation accuracy by utilizing the long term behaviour of deviations between modelled and measured values to automatically adjust system parameters to better match the measurement values. Gassco uses the online simulation systems to provide the following main functions:

- Reliable overview of hydraulic and quality pipeline data around subsea mixing points /material specification breaks with no physical instrumentation.
- Accurate tracking of the gas quality in all pipeline networks, both online, in the past and from look-ahead (future) results.
- Predict how long the pipeline may be able to survive a shutdown or maintenance period without impacting the delivery of gas to customers at the pipeline delivery points by giving the control room operators a tool that can simulate from the current conditions with nominations in the pipeline networks.
- Capacity management to determine in advance commitments that can be made to the suppliers and allow control room operators to drive capacity closer to actual pipeline limits to minimize effect of plant disruptions.
- Leak detection.

The look-ahead calculations provide forecasting of results based on the current calculated state of the system and planned future shipper nominations. Figure 8 gives an example of the look-ahead modelling. This tool is very useful for pipeline controllers to plan future actions in order to maximize gas delivery without risking any safety violations.

Over a twelve month period, the simulation systems have helped Gassco generate an additional revenue in the range of 100 MSCM valued at more than US$ 7.5 million [20].

CONCLUSIONS

It is essential for offshore pipeline operators to understand what is happening within their pipelines. Since the cost of subsea instrumentation is very high, the application of advanced leak detection and hydraulic simulation technologies can provide the operators with useful information and peace of mind. This paper has shown that with limited measurements on oil/gas platforms and onshore only, accurate calculations of flow, pressure and temperature along the subsea pipelines can be provided. They serve as virtual instruments to these pipelines. The statistical volume balance leak detection system monitors the integrity of these pipelines reliably. The fast detection and accurate location of leaks help the pipeline companies minimize the consequence of a leak, thus protect the environment and their reputation.

ACKNOWLEDGMENTS

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NOMENCLATURE

- BSCM - Billion Standard Cubic Meters
- DCS – Distributed Control System
- LDS – Leak Detection System
- MSCM – Million Standard Cubic Meters
- SCADA – Supervisory Control and Data Acquisition
- RTTM – Real Time Transient Model
- SPRT – Sequential Probability Ratio Test

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