Why is pipeline leak detection more than just installing a flowmeter at inlet and outlet?

1 Paper details
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2 Abstract
Today the need for pipeline leak detection is clear and numerous different systems are commercially available. Most of these systems use measurement of flow, pressure and temperature; these systems are called ‘internal systems’, since no extensive hardware along the pipeline has to be installed. This paper starts with an overview of the most commonly used internal systems and a summary of the (dis)advantages of each system.

A software demo is used to explain why leak detection is more then just installing a flowmeter at inlet and outlet. The demo will, for example, show that flow is very transient during start-up of a pipeline and thus limits the minimum detectable leak rate of most internal leak detection systems. Unfortunately start-up is also the phase where most of the spontaneous pipeline leaks occur, after all pressure is increased during start-up.

Based on the aforementioned demo it will be shown why PipePatrol E-RTTM (KROHNE’s high-end system) maintains it’s sensitivity during transient condition, where more basic systems, such as PipePatrol Statistical (KROHNE’s basic system), have to raise the limit for the minimum threshold. A consideration will be made what system should be used for which application. High-end systems allow faster detection of smaller leaks, but can only do so if the SCADA system provides sufficient information.

The two most widely used principles for leak localization, the gradient intersection and the wave propagation method, will be explained using actual data from a 31 km long liquid pipeline. It will be clarified how the SCADA refresh rates influences the accuracy of the leak localization.

3 Different leak detection systems
Figures 1 gives an overview of the different categories in which leak detection systems can be distinguished. A first distinguishing can be made between continuously and non-continuously working systems. The continuously working system can again be divided in external and internal system. Further details are given below.

Non-continuously working system
Non-continuously working systems are usually inspections that are carried out on regular intervals. Depending on the type of the inspection, the pipeline operation can continue (e.g. in case of inspection by helicopter) or the pipeline operation has to be stopped (e.g. in case of intelligent pigging). Non-continuously working systems are used in a completely different application area when compared to continuously working systems, a further clarification is therefore not given in this document.

Externally based systems
External systems are called external because sensors have to be installed on the ‘outside’ of a pipeline. Typical external systems are vapour sensing cables, temperature sensitive fibre optic cables and acoustic emission detectors. Due to the high installation costs the use of external systems is usually restricted to high risk areas such as nature protection areas and near rivers. Externally based systems are not further clarified in this document.
Internally based systems
Internal systems are called internal because they use measurements of flow, temperature and pressure to detect a leak. No additional ‘outside’ sensors have to be installed for these systems. Today there are numerous techniques on the market, which sometimes are a combination of different techniques. In this document we focus on the main techniques as described in API 1130 (American Petroleum Institute).

Volume balance
The simplest form of leak detection is volume balancing. Here simply two flowmeters are installed, one at inlet and one at outlet. If the difference between inlet volume and outlet volume exceeds a predefined threshold a leak alarm is given. Since this method does not compensate for pressure and temperature, nor for line pack (the volume or mass that is stored in the pipeline), this system is only able to detect catastrophic leaks. Nowadays volume balancing is rarely used due to its limited performances.

Mass balance
In mass balance application the mass flow at inlet and outlet is compared. If the difference exceeds a predefined threshold a leak alarm is given. Mass balance compensated for pressure and temperature, it however does not compensate for changes in line pack.

Compensated Mass balance
If also the changes in line pack (mass that is stored in a pipeline) are considered, we speak about compensated mass balance. Using the readings of flow, pressure and temperature a simple static model can be used to estimate the line pack. This enables a simple calculation; mass out minus mass in minus changes in line pack. If the outcome of this calculation crossed a threshold a leak alarm is given. Since compressibility, pipeline expansion, pipe wall friction, temperature exchange, etc are usually ignored while calculating the line pack, compensated mass balance systems have limitations under transient conditions in a liquid pipeline and cannot be used for gas pipelines.

Pressure monitoring
Different forms or pressure monitoring exist, they are however based on the same ground principle. Spontaneous and big enough leaks result is sudden changes of pressure (and flow) at inlet and outlet. Usually these sudden pressure drops are the result of a leak, however they also might occur in (heavy) transient pipeline conditions. By means of filtering techniques the pressure waves are filtered in order to distinguish between an operational pressure change and a leak. Since pressure waves damp out when they have to travel a longer length, additional pressure sensors along the pipeline might be required.
**Statistical analysis (used in KROHNE PipePatrol SMB)**
Statistical analysis applies a statistical technique (Wald’s Sequential Probability Ratio Test, SPRT) to interpret the results of a mass balance or compensate mass balance system. If long enough time is allowed, the difference between inlet and outlet flow in a (compensated) mass balance system will be a Gaussian distribution. SPRT is subsequently used to interpret the Gaussian distribution. This systems work well in stationary conditions, however requires longer time (i.e. several hours) to detect a leak under transient conditions.

**(Extended) Real Time Transient Modeling (used in KROHNE PipePatrol E-RTTM)**
Real Time Transient Modeling (RTTM) is based on a series of algorithms that allow calculation of the flow along the entire pipeline based on pressure and temperature readings at inlet and outlet of a pipeline. This calculated flow is compared with a measured flow. In contradiction to all other internally based systems, RTTM based systems do not directly compare inlet flow with outlet flow (i.e. they compare measured and calculated flow at inlet to each other and compare measured and calculated flow at outlet to each other). When the model is extended with leak pattern recognition, the principle is called E(xtended)-RTTM.

4 Transient Flow Conditions
Speaking about leak detection systems immediately raises the issue of flow regimes; is the system operated in stationary or transient flow conditions. A gas pipeline will virtually always show heavy transient flow due to the compressibility of the gas (see figure 2). A liquid will show (heavy) transient flow during and after operational changes. During normal pumping conditions a liquid will show minor transient due to pipe wall friction, reflection of pressure waves and temperature differences. Leak detection during stationary conditions is relatively easy, however leak detection during transient conditions is more difficult. Unfortunately this is where spontaneous leaks typically occur as they are the effect of a change in pressure or flow. Considering the flow regime might be the most important issue when selecting a leak detection system.

![Figure 2: typical pipeline behaviour in a gas pipeline during normal pumping conditions over approximately 12 hours. Flow changes constantly due to a changing outlet demand and changes in the line pack.](image)

**False alarms**
The number of false alarms is a very critical item. After several false alarms there is a danger that the operator will ignore further leak alarms or will even switch the system off. Bottom line is that leak detection system should not give false alarms under any circumstances!
Specifications
According to API 1155 Leak detection systems should be evaluated using the following four items;
- sensitivity (minimum dateable leak rate and time required to detect the leak)
- reliability (number of false alarms per year)
- accuracy (accuracy of leak location and leak rate calculation)
- robustness (Continue operation if something goes wrong, e.g. a sensor failure)

When speaking about sensitivity, it is important to know how small a leak can be detected but also how fast this can be done. A leak detection system that can detect small leaks (e.g. 1% of nominal flow) sounds promising, but if it takes two days before it detects this leak the 1% claim is of little interest. Sensitivity figures should be interpreted carefully, basically they are only meaningful if they refer to the pipeline conditions (transient or stationary) and the time required to detect a leak.

In case of for example a sensor failure, the system should definitively not give a false alarm. Ideally the system should remain in operation, possibly with a reduced sensitivity. Redundant sensors might be installed to overcome a reduction in sensitivity due to a sensor failure; a false alarm should be avoided at all costs. In case leak localisation is included in the leak detection system it is important that this localisation is accurate enough to access the location with limited effort and within a reasonable time span.

Over specifying - a theoretical or practical approach
A comparison of different types of systems shows that most systems promise impressive sensitivity and accuracy figures. As explained an analysis of the figures should incorporate whether they include stationary or transient pipeline operation and the times required to detect a leak. Secondly it should be considered whether these figures come from a purely technical calculation or can they be backed-up with field test data.

A simple example can be given for leak localization. Leak localization is typically done by analyzing pressure waves. Since pressure waves travel with the velocity of sound, their typical velocity in a liquid hydrocarbon is approximately 1300 m/s. When a leak localization of ± 10 meters is specified, this means the refresh rate of the pressure reading should be 10/1300 = 7 ms (milliseconds). In a purely mathematical approach, ignoring all transients in the line, this localization is possible. In an industrial application however, this scenario is unrealistic. First of all because a pipeline will never show the theoretical pure stationary pipeline conditions, but also because data refresh rates are typically between 0.5 and 30 seconds. Even a refresh rate of 0.5 seconds in a (theoretical) purely stationary environment physically restricts the minimum achievable accuracy to 1300*0.5 = ± 650 meter.

More information on comparing different leak detection systems can be found on the following, independent, websites:
API, American Petroleum Institute, www.api.org
API 1130: Computational Pipeline Monitoring for Liquid Pipelines
API 1155: Evaluation Methodology for Software Based Leak Detection
PSIG, Pipeline Simulation Interest Group, www.psig.org
Paper 0301: Leak detection and Locating – A Survey

5 E-RTTM, Extended Real Time Transient Modelling
E-RTTM is a further development of conventional RTTM technology. The development comprises the introduction of a leak pattern recognition algorithm to avoid compromising between a minimal detectable leak rate and a maximum allowed number of false alarms. A second enhancement is the introduction of Statistical Analysis based leak detection as a back-up option in case of multiple sensor failure.
Basic Explanation of RTTM

PipePatrol-RTTM permits the calculation of flow, pressure, density and temperature along an entire pipeline. Inputs are pressure and fluid temperature at inlet and outlet, and one ground temperature reading (or water temperature for sub-sea pipelines) at either inlet or outlet of the pipeline. Inlet and outlet density are usually calculated from pressure and temperature or, in case of a non-constant standard density, is measured directly. For liquid hydrocarbons API 2540 can be used. For gases, the adequate thermodynamic state equations can be used. With RTTM the (calculated) flow and pressure at any point in the pipeline are known entities.

The calculated flow or pressure is subsequently compared to a measured flow or pressure (from a flowmeter at any point in the line or a pressure sensor somewhere other than at inlet and outlet). Typically RTTM is used to compare measured and calculated flow at inlet and outlet, since flowmeters are usually installed at this position. In case additional measurement instrumentation is available (e.g. intermediate pressure sensors), the readings of these instruments can be compared to a calculated value, thereby improving the reaction time of the leak detection system.

Figure 3 shows a typical RTTM approach where measured and calculated flow at inlet and outlet are compared. The measured and calculated flow at inlet (lower two lines) and the measured and calculated flow at outlet (upper two lines) are shown in figure 3. In figure 4, the upper graph shows the difference between calculated and measured flow at outlet, called the outlet residual. The bottom graph shows the difference between calculated and measured flow at inlet, called the inlet residual. In a pipeline with no leaks, the residuals should be zero (any fluctuating around zero being due to inaccuracies in the field instruments) since the RTTM calculates flow using a model that describes a leak-free pipeline. Note that the presented data are true data coming from a transiently operated gas pipeline.

![Figure 3: Measured and calculated flow at inlet and outlet](image)

![Figure 4: Flow residuals for inlet and outlet](image)
Leak Pattern Recognition
Combining a classical RTTM approach with a leak pattern recognition algorithm results in E-RTTM. If a predefined threshold (i.e. the minimum detectable leak rate) is exceeded, the leak pattern recognition algorithm uses statistics to determine whether the residual shows the dynamic effect that is typical for a spontaneous leak. If this effect is shown, a leak alarm will be given. If this effect does not show, the deviation is most likely caused by a drifting sensor and, after the sensor data has been analysed, a sensor warning will be given so the operator is aware that a sensor needs attention.

Figure 4 – Typical leak pattern, vs sensor drift

6 Leak localization on a liquid pipeline
This chapter describes a multi-product liquid pipeline that transports refined liquid hydrocarbons. The pipeline has three intermediate valve stations and one of these stations was used to conduct leak trails. The Intermediate valve stations do not have permanent instrumentation installed as they are only used for emergency shut-down.

Application details
Details of the application can be found below. Field instrumentation was already present and sent the measured data to the existing data communication system. The PipePatrol Monitoring Station was installed in the control room and communicates to the SCADA system via OPC. A layout of the instrumentation can be found in figure 5. The VoS (velocity of sound) signal from the ultrasonic flowmeters was used to identify the product entering the pipeline. This product identification is required for batch tracking and for informing the RTTM when a new product (with a different density and viscosity under standard conditions) enters the pipeline.

Pipeline data
• Length 31.5 km (20 miles)
• Diameter DN 250 (10")
• Mainly underground, partially above ground
• Bi-directional

Instrumentation
• Flow and VoS at inlet and outlet (Ultrasonic Flowmeters)
• Pressure at inlet and outlet
• Temperature of product at inlet and outlet
• Temperature of ground at inlet and outlet

Flow data
• Nominal flow of 300 m³/h
• Nominal pressure 18 Bara (at inlet side)
• Transient behaviour during batch changes, start-up and shut-down
Leak trials
During the trial period the line was pumping naphtha. Trials were held at valve station 3 (22.4 km from the inlet) and the released naphtha was pumped into an empty tanker truck. The leak rate was set at 1.5% of the nominal flow (note that the minimum detectable leak rate for this system is considerably lower), thus creating a leak flow of approximately 5 m$^3$/h. The test was carried out 3 times consecutively, whereby each leak was detected within 30 seconds and a confirmed leak alarm was given within 60 seconds.

Figure 6 below shows the inlet and outlet residual during one of the leak trial periods. The leak started at 11:45 (42280 s after midnight) and ended at 11:50 (42650 s after midnight). Since the leak was positioned at 22.4 km from the inlet in a 31.5 km long pipeline, 71% of the leak effect is seen at the outlet side (the leak is closed to the outlet) and 29% of the leak effect is seen at the inlet side.

Leak localisation and leak rate calculation
Two different mechanisms were applied to calculate the leak location. Figure 7 shows the results from the Wave Propagation Method (22246 meters); Figure 8 the results of the Gradient Intersection Method (22005 meters). Averaging these results gives a leak position at 22125 meter from inlet (normally only one result is shown), with the actual leak at 22400 meter the leak localisation error is 275 meter or 0.87% of the pipeline length.

Time required to localise the leak with the wave propagation method is 60 s, the time required to locate the leak with the gradient intersection method is about 4 minutes since some time is required for the leak flow to stabilise. Figure 18 shows the calculation of the leak rate. Some time is required for the leak flow to stabilise and 220 s after the leak was detected, the leak flow was calculated to be 5.3 m$^3$/h.
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