State-of-the-Art in Leak Detection and Localisation

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Abstract

Many fluids transported by pipelines are hazardous. It is therefore often necessary to install leak detection (and localization) systems (LDS), especially due to legal regulations like

- the "Code for Federal Regulations (CFR) Title 49 Part 195" [1], API 1130 2nd Ed. [2], both for the USA, or
- the "Technische Regeln für Fernleitungen" (TRFL) (Technical Rules for Pipelines) in Germany [5].

This paper gives an overview of methodologies, methods and techniques for leak detection and localization; [6] and [7] are two other interesting sources giving an overview.

Some remarks concerning (legal) regulations both for the USA and for Germany will be shown in chapter 1. Chapter 2 summarizes the requirement to LDS considering

- reliability,
- sensitivity,
- accuracy, and
- robustness.

These terms had been defined with respect to LDS within API 1155 [3], and will be explained in some detail within this chapter 2.

External systems. External based LDS (due to API 1130 2nd Ed.) use local leak sensors to generate a leak alarm. Acoustic emission detectors, fiber optical sensing cable, vapor sensing cable and liquid sensing cable based systems are shortly presented in chapter 3.

Internal systems. Internal based LDS (also due to API 1130 2nd Ed.) use normal field sensors (e.g. flowmeters) for leak detection and sometimes leak localization. A significant part of the paper (chapter 4) deals with these internally based systems like

- balancing systems (line balance, volume balance, compensated mass balance etc.),
- Real Time Transient Model LDS (RTTM-LDS),
- pressure/flow monitoring, and
- statistical analysis LDS.

Different methods for leak localization (gradient intersection method, wave propagation analysis etc.) will be shown in chapter 5.

Extended RTTM. The presentation of an Extended RTTM approach (E-RTTM) combining advantages of conventional RTTM LDS and statistical systems follows in chapter 6, together with the demonstration of applicability by means of two examples,

- a liquid multi-batch pipeline, and
- a gas pipeline.

PipePatrol. The University of Applied Sciences in Gelsenkirchen and KROHNE Oil & Gas B.V. from the Netherlands (KOG) closely work together on the field of leak detection. The outstanding properties of the E-RTTM technology therefore motivates KOG to choose E-RTTM for PipePatrol, the KOG leak detection and localization system.

1 Regulatory Framework

Companies operating pipelines transporting hazardous fluids (e.g. liquids or gases) often have to consider a dedicated regulatory framework. Examples are

- Code for Federal Regulations (CFR) Title 49 Part 195 [1] (USA)
- API 1130 2nd Ed. [2] (USA), and
- "Technische Regeln für Fernleitungen" (TRFL) (Technical Rules for Pipelines) [5] (Germany).

1.1 API 1130 2nd Edition (USA)

The 2nd Edition of API 1130 "Computational Pipeline Monitoring for Liquid Pipelines" was published from the American Petroleum Institute in November, 2002, [6]. Other regulations like the "Code for Federal Regulations (CFR) Title 49 Part 195" [1] refer to API 1130. The API 1130 focuses on the design, implementation, testing and operation of CPM systems; it is limited to single-phase liquid pipelines. It defines a CPM-system as an "algorithmic approach to detect hydraulic anomalies in pipeline operating parameters". The technical overview section introduces to methodologies of CPM-systems, classifying them into

- externally based leak detection systems, and
- internally based CPM systems.

Externally based systems. Externally based systems use local sensors, generating a leak alarm. System costs and complexity of installation usually are high; applications therefore are limited to special high-risk areas, e.g. near rivers or nature protection areas. Examples for such a type of LDS are acoustic emission detectors monitoring noise levels and location and vapor sensing cables, sensing gas or hydrocarbon vapor near a leak.

Internally based systems. Internally based systems utilize field sensors (e.g. for flow, pressure and fluid temperature) to monitor internal pipeline parameters. These field signals are used for inferring a leak. The classical line balance method balancing inlet and outlet volume flow is an example.

Other sections of the API 1130 cover topics like

- field instrumentation, SCADA/Communication, data presentation,

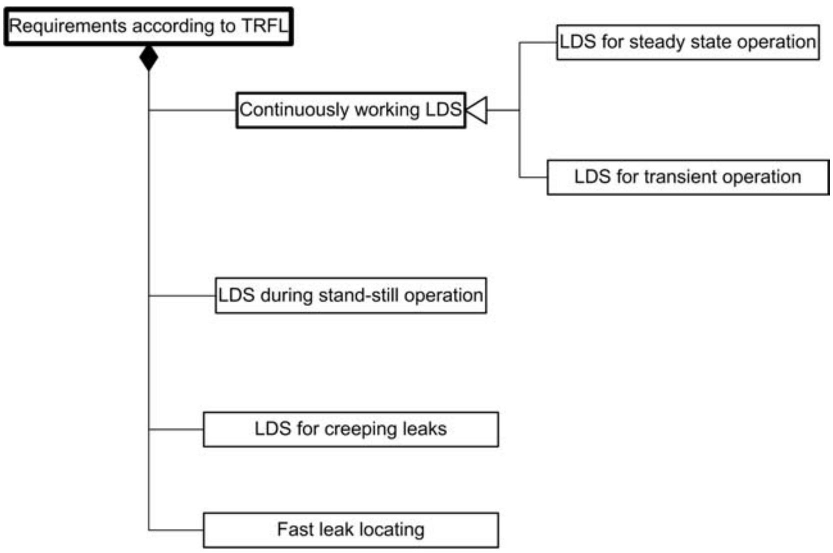
- operation, maintenance and testing, and
- descriptions of types of internally based CPM systems.

1.2 TRFL (Germany)

TRFL is the abbreviation of "Technische Regel für Fernleitungsanlagen" (Technical Rule for Pipeline Systems); it is the successor of the TRbF 301, "Technische Richtlinie für brennbare Flüssigkeiten" (Technical Guideline for flammable Liquids). The TRFL summarizes requirements for pipelines being subject of official regulations. It covers

- pipelines transporting flammable liquids,
- pipelines transporting liquids being dangerous for water, and
- many pipelines transporting gas.

Figure 1: Requirements concerning LDS according to TRFL.



The TRFL is divided into the two parts "Operation" and "Constitution" of pipeline systems. Only a small part is concerned with leak detection and localization, focusing to the specification of measures necessary in order to detect and locate leaks. Five different LDS and LDS functions are required[1], see Figure 1:

- Two independent LDS for continuously operating leak detection during steady state operation. One of these systems or an additional one must also be able to detect leaks during transient operation, e.g. during start-up of the pipeline.
- One LDS for leak detection during stand-still operation.
- One LDS for creeping leakages.
- One LDS for fast leak localization.

[1] It is partially possible to combine different LDS functions into one LDS device.

The TRFL is focused to general requirements necessary to detect and locate leaks; it gives not much information about technical aspects like design or implementation of LDS.

2 Requirements to LDS

API 1155 [3] provides a common framework to evaluate the performance of LDS. This simplifies the selection of appropriate LDS meeting the customer requirements. API 1155 defines four performance metrics:

2.1 Reliability

Reliability (due to API 1155) is defined as a measure of the ability of the LDS to render accurate decisions about the possible existence of a leak on the pipeline, while operating within an envelope established by the LDS design. It follows that reliability is directly related to the probability

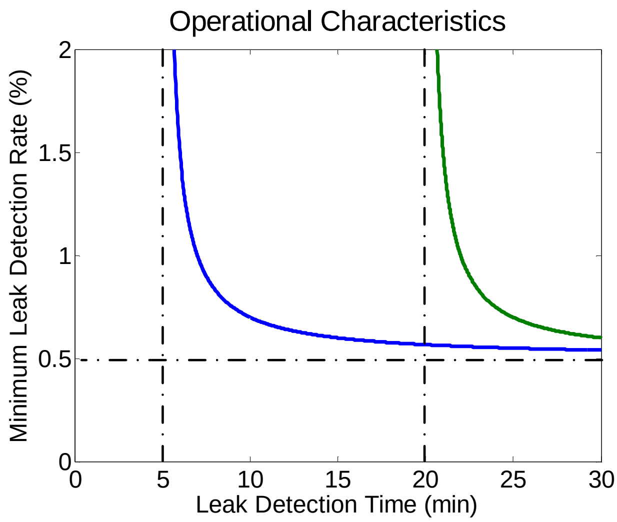
- to detect a leak, given that a leak in fact exists, and
- to incorrectly declare a leak given that no leak has occurred.

A system is considered to be reliable if it consistently detects actual leaks without generating incorrect declarations.

2.2 Sensitivity

Sensitivity (due to API 1155) is defined as a composite measure of the size of leak that a LDS is capable to detect, and the time required for the system to issue an alarm. Minimum detectable leak rate and leak detection time depend on each other. Smaller minimum leak detection rates require longer leak detection times, and larger minimum leak detection rates permit smaller leak detection times. The performance of a LDS will best be described using an Operational Characteristic Plot.

Figure 2: Evaluating sensitivity using the operational characteristic plot.



There are some important things to note:

- For very long leak detection times, for both LDS, the minimum leak detection rate converges asymptotically to a minimum limit value, the smallest possible leak detection rate. This value mainly depends from the accuracy of the flowmeters and therefore is nearly independent from the LDS used.

- If detection time decreases, the minimum leak detection rate increases for both LDS. LDS #1 shows a much better performance (smaller minimum leak detection rates) than LDS #2.

2.3 Accuracy

LDS may provide additional leak information like leak location and leak rate. The validity of these leak parameter estimates constitutes another measure of performance referred to as accuracy.

2.4 Robustness

Robustness (due to API 1155) is defined as a measure of the LDS ability to continue to operate and provide useful information, even under changing conditions of pipeline operation, or in condition where data is lost or suspect. A LDS is considered to be robust if it continues to function under such less then ideal conditions. Robust LDS typically are able to tolerate sensor failures using some kind of redundancy evaluation.

3 Externally Based Systems

There are many possibilities to classify externally and internally based systems; we follow the API classification scheme [6].

Local leak sensors of externally based systems generate a leak alarm which e.g. can be evaluated by SCADA-systems. This kind of LDS is characterized by a very good sensitivity to leaks and is very accurate with respect to the leak localization. On the other side, system costs and complexity of installation usually are high; applications therefore are limited to special high-risk areas, e.g. near rivers or nature protection areas.

3.1 Acoustic emission detectors

Escaping liquids creates an acoustic signal as it passes through a perforation in the pipe. Acoustic sensors affixed to the outside of the pipe monitor internal noise levels and location, creating a baseline acoustic “fingerprint” of the line. When a leak occurs, the resulting low frequency acoustic signal is detected and analyzed. Deviation from the baseline “fingerprint” would signal an alarm [8]. The received signal is stronger near the leak site thus enabling leak localization, see below.

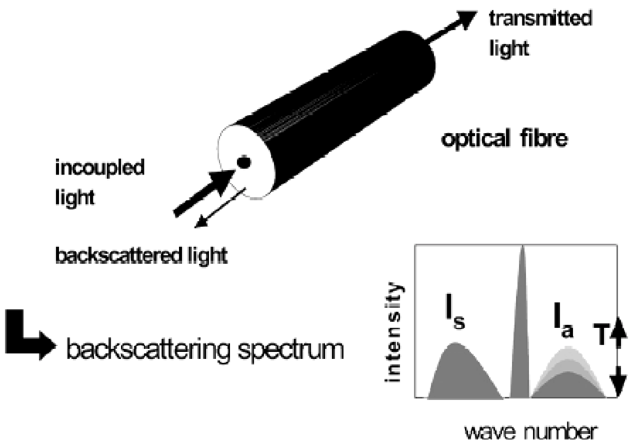
3.2 Fiber optic sensing cables

The fiber optic sensing leak detection method involves the installation of a fiber optic cable along the entire length of the pipeline.

The substances to be measured come into contact with the cable in case of a leak occurrence, changing the temperature of the cable. The distributed fiber optical temperature sensing technique offers the possibility to measure temperature along the pipeline.

Figure 3: Leak detection and localization using optical fiber. ©GESO GmbH, Jena

(Germany).

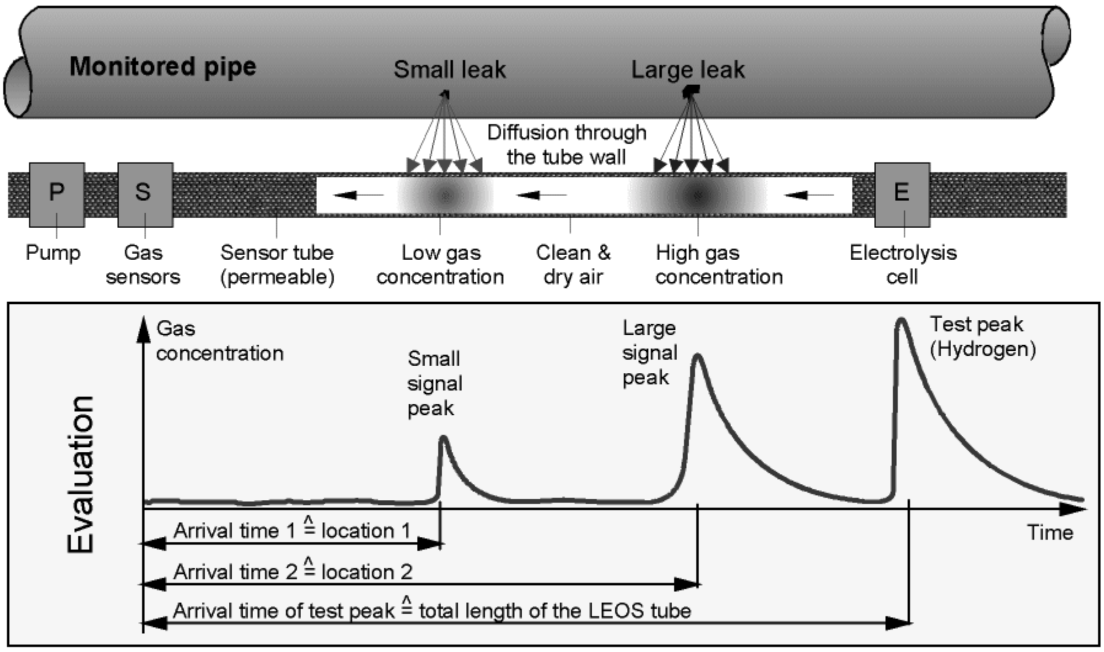


This technique is based on the Raman Effect and the so-called Optical Time Domain Reflectometry (OTDR). A pulsed laser is coupled into the optical fiber which is the sensing element. In the fiber the photons interact with the molecules of the fiber material. Therefore, the laser light is scattered as the laser pulse propagates through the fiber owing to changes in density and composition of the fiber as well as to molecular and bulk vibrations. Some of the photons are scattered backwards. The spectrum of the backscattered will be analyzed. The spectral analysis is combined with measuring propagation time of the laser pulses along the fiber (radar principle) because the velocity of the light in the fiber is known. Scanning the entire length of the fiber by short intervals (e.g. 3ft) the temperature profile along the fiber is determined. Assuming that in case of a leak the temperature locally changes at the sensing cable position, leaks can be detected and localized [9].

3.3 Vapor or liquid sensing tubes

The vapor or liquid sensing tube based leak detection method involves the installation of a tube along the entire length of the pipeline.

Figure 4: Leak detection and localization using vapor sensing tube. ©Framatome ANP, Erlangen (Germany).



This tube is highly permeable to the substances to be detected in the particular application. If a leak occurs, the substances to be measured come into contact with the tube in the form of vapor, gas or dissolved in water. The tube is pressure-tight and is filled with air (at atmospheric pressure). In the event of a leak, the leaking substance diffuses into the tube due to the concentration gradient. After a certain period of time, the inside of the tube produces an accurate image of the substances surrounding the tube, regardless whether the tube is installed in air, water or in the ground.

In order to analyze the concentration distribution present in the sensor tube, a pump pushes the column of air in the tube past a detection unit at a constant speed, thus recording the measured level as a function of the pumping time. The concentration profile is not affected by the pumping action. The detector unit at the end of the sensor tube is equipped with gas sensors. Every increase in gas concentration results in a pronounced "leak peak". The height of the peak is proportional to the concentration of the substance and is therefore an indication of the size of the leak (a small leak produces a small peak and a large leak produces a large peak).

An electrolytic cell at the end of the detected line is used to inject a specific volume of test gas prior to each pumping action. This gas is transported through the entire length of the sensor tube together with the air. When the test gas passes through the detector unit, it generates a marking peak or end peak. Its arrival serves as a control marker to indicate that the entire air column contained in the sensor tube has passed through the measuring station. The end peak is thus an indication of the overall length of the sensor tube. Based on the ratio of the travel time of the leak peak to that of the end peak, the leak location can be accurately calculated [10].

3.4 Liquid sensing cables

Liquid sensing cables are buried beneath or adjacent to a pipeline and are specifically designed to reflect changes in transmitted energy pulses as a result of impedance differentials included by contact with hydrocarbon liquids. Safe energy pulses are continuously sent through the cable. The pulses are reflected and a baseline reflection "fingerprint" is measured.

When a leak occurs, the cable is saturated with fluid, altering the impedance of the sensing cable, which in turn alters the reflection pattern returned. Deviation from the baseline "fingerprint" would signal an alarm. Measuring time delay between input pulse and reflected pulse enables leak localization. Specific cable types are chosen for each application based on the specific fluid being monitored [7].

4 Internally Based Systems

4.1 Balancing systems

These kinds of LDS use the principle of mass conservation: Mass is conserved if there is no leak:

$$\dot{M}_I(t) - \dot{M}_O(t) = \frac{dM_L}{dt} \tag{1}$$

with mass flow $\dot{M}_i$ and $\dot{M}_O$ at inlet (I) and outlet (O), respectively, and the mass M_L stored in the line. In general, line fill[2] M_L for a pipeline of length *L* changes over time due to changes of the fluid density ρ and cross-sectional area *A* according to

$$\frac{dM_L}{dt} = \frac{d}{dt}\int_0^L \rho(x)A(x)dx = \int_0^L \frac{d}{dt}\langle \rho(x)A(x)\rangle dx \tag{2}$$

with position coordinate *x*, $0 \le x \le L$. ρ changes according to the relation $\rho(x) = \rho(p(x), T(x))$ (corresponding to the thermodynamic PVT equation $p = p(\rho, T)$), whereas *A* changes according to the relation $A(x) = A(p(x), T(x))$ as a result of the pipeline deformation.

Line balance. If ρ and A are assumed to be constant, $\rho = \rho(p,T) = \rho_L$ and $A = A(p,T) = A_L$, then $dM_L/dt = 0$ and eq. (1) can be rewritten into

$$\dot{M}_I(t) - \dot{M}_O(t) = 0 \tag{3}$$

Additionally assuming equal and constant densities $\rho_I(t) = \rho_I = \rho_L$ and $\rho_O(t) = \rho_O = \rho_L$ for inlet and outlet mass flow, respectively, and introducing volume flow $\dot{V}$ with $\dot{M} = \rho\dot{V}$, we finally get

$$\dot{V}_I(t) - \dot{V}_O(t) = 0\,. \tag{4}$$

The estimated imbalance[3] $R(t) \equiv \dot{V}_I(t) - \dot{V}_O(t)$ can be compared with

[2] Terms like „line pack" or „pipeline inventory" are also used.
[3] Also referred as „residual".

$$R \begin{cases} < A & \Rightarrow \quad no\ leak \\ \geq A & \Rightarrow \quad leak \end{cases} \tag{5}$$

against a threshold A to evaluate the leak alarm. This is the classical line balance method.

Volume balance. Using a representative bulk modulus of elasticity K, assuming a pipeline without deformation and using average line pressure p_L as well as an average line fluid temperature T_L allows for a simple line fill calculation $M_L = M_L(p_L, T_L)$ and $V_L = M_L / \rho_L$ with some kind of average density ρ_L of the fluid along the pipeline. The estimated imbalance R can be enhanced to

$$R(t) \equiv \dot{V}_I(t) - \dot{V}_O(t) - \frac{dV_L}{dt} \tag{6}$$

Volume balance permits very simple line pack elimination.

Compensated mass balance. Returning to eq. (1), a more rigorous approach leads to the residual definition

$$R(t) \equiv \dot{M}_I(t) - \dot{M}_O(t) - \frac{dM_L}{dt} \tag{7}$$

with dM_L / dt according to eq. (2). Dividing the pipeline into n segments of individual length Δx_i where p, T and ρ can be regarded as uniform results in the line fill calculation

$$M_L = \int_0^L \rho(x) A(x) dx \approx \sum_1^n \rho_i A_i \Delta x_i \ . \tag{8}$$

with uniform segment density ρ_i. For liquids (especially oil products), ρ_i can be calculated using the relation

$$\rho = \rho(p, T) = C_p(p - p_0, T - T_0) \cdot C_T(T - T_0) \cdot \rho_0 \tag{9}$$

with volume correction factors for pressure C_p and C_T for temperature [11]. ρ_0 denotes the liquid density at some reference point p_0, T_0. Using eq. (9) together with the cross-sectional area $A = A(p, T)$ (see [11]), line fill eq. (8) can be computed numerically providing segment variables p_i, T_i, e.g using additional measurements or a steady-state model of the pipeline.

Model compensated mass balance. Using Real-time Transient Models (RTTM) allow for the computation of density $\rho(x,t)$ along the pipeline, see below [6]; model inputs are a choice of variables p_I, $\dot{M}_I(\dot{V}_I)$, ρ_I, T_I at inlet and p_O, $\dot{M}_I(\dot{V}_I)$, ρ_O, T_O at outlet. Therefore, line fill M_L in eq. (8) can be computed using model output $\rho(x,t)$. From a theoretical point of view, this is the most rigorous balancing approach.

4.2 RTTM

Using the increasing computing power of modern digital computers, it is possible to calculate in real time the profiles for flow v[4], pressure p and density ρ (or temperature T) along the pipeline. This requires solving a partial differential equation (PDE) system as a result of applying continuity equation [12]

$$\frac{d\rho}{dt} + \rho \cdot \frac{\partial v}{\partial x} = 0\,, \tag{10}$$

momentum equation

$$\frac{dv}{dt} + \frac{1}{\rho} \cdot \frac{\partial p}{\partial x} + f_D = 0\,, \tag{11}$$

and energy equation

$$\frac{dh}{dt} - \frac{1}{\rho} \cdot \frac{dp}{dt} - l_L = 0\,. \tag{12}$$

Remarks:

- These equations describe (for simplicity) one-dimensional (location x) transient (time t) single-phase fluid (liquid and gas) flow in a single pipeline segment without diffusion. It is a hyperbolic type PDE system.
- Appropriate thermodynamic state equations $p = p(\rho, T)$[5] and $h = h(\rho, T)$ are required to eliminate enthalpy h, leading to three equations with three unknowns ρ, v and p.
- Drag force f_D per unit mass includes force of gravity per unit mass and friction force per unit mass: $f_D \equiv f_G + f_F$.
- Losses l_L per unit mass includes heat flow per unit mass and dissipative losses per unit mass: $l_L = l_Q + v \cdot f_F$.
- The computation of heat flow per unit mass l_Q requires an additional thermal model.
- Special model extensions could be required for multi-phase conditions and other non-standard conditions (slag-line, usage of drag reducing agents, DRA).

Up to now, there is no known analytical solution. Therefore, numerical algorithms have to be used instead [13]. Examples are method of characteristics (MOC) and finite difference, finite volume and finite element methods.

The resulting numerical algorithm is of boundary value problem type with three boundary conditions required.

Friction force. Using Darcy-Weisbach equation, friction force per unit mass f_F for a pipeline with diameter D is given by

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[4] Relation to volume flow is given by $\dot{V} = A \cdot v$.
[5] Alternative formulations are $\rho = \rho(p, T)$ and $T = T(\rho, p)$.

$$f_F = f\,\frac{v|v|}{2D} \tag{13}$$

with Darcy-Weisbach friction factor *f* [14], often calculated for turbulent flow using Colebrook-White formula [15]

$$\frac{1}{\sqrt{f}} = -2\cdot\log\left(\frac{1}{3.7}\frac{\varepsilon}{D} + \frac{2.523}{\mathrm{Re}\cdot\sqrt{f}}\right) \tag{14}$$

with Reynolds number Re and roughness height ε; see [15] and [16] for alternative turbulent flow formulas. For laminar flow, eq. (14) simplifies to

$$f = \frac{64}{\mathrm{Re}}. \tag{15}$$

State equations. It is interesting to see, that the thermodynamic PVT-equation $p = p(\rho, T)$ and $h = h(\rho, T)$ are the only fluid specific equations in eq. (10-12), thereby differentiating liquids and gases; see [19] for a further discussion of improved PVT-equations $p = p(\rho, T)$.

Liquids. Density $\rho = \rho(p, T)$ of liquids mainly depends on temperature *T*. Nevertheless, the dependency of pressure *p* cannot be neglected because this kind of compressibility introduces transient effects like pressure and flow waves moving with the speed of sound

$$c^2 \equiv \frac{dp}{d\rho}. \tag{16}$$

Liquid products like crude oils or fuel oil often are mixtures of different components, so general, simple PVT-relations $\rho = \rho(p, T)$ are not obtainable. See e.g. API Standard 2540 [4] for tables describing $\rho = \rho(p, T)$ by polynomial curve fitting methods.

Gases. The simplest approach for an ideal gas results in [17]

$$p = p(\rho, T) = 1\cdot\frac{R}{M}\cdot\rho\cdot T \tag{17}$$

with gas constant *R* and molecular weight *M*. Another suitable and for must cases sufficient accurate approach for pure gases is the PVT equation due to Redlich-Kwong-Soave (RKS, [18]).

Simplifications. Simpler mathematical models can be derived using additional assumptions like adiabatic or isothermal flow [20], sometimes reducing the order of the PDE system eq. (10-12). For liquids, neglecting heat transfer and the conversion of frictional work into thermal energy leads the water hammer equations [14], a 2nd order PDE system.

Multi-phase flow, slack line. Condensation from gas into liquid often can be observed in gas pipelines from off-shore wells, resulting in a two-phase gas-liquid flow. Condensate pipelines that are liquid only due to pressurization or crude pipelines that run through mountainous terrain exhibit the opposite problem: slack line, introducing some volume of gas in the pipeline. Both phenomena have a significant impact on the hydraulic operation of the pipeline [13]. The modeling of multi-phase flow requires the introduction of multi-component transport and the model being capable of performing the individual boiling or condensation of each of the individual components.

Drag reducing agents, DRA. DRAs improve the delivery capability and reduce the cost of pressurization by reducing the pressure drop per unit length of pipeline. The impact of DRAs can be modeled by [13]

$$f'_F = \kappa \cdot f_F = \kappa \cdot \frac{f\, v|v|}{2D} \tag{18}$$

using friction force per unit mass f_F according to eq. (13). κ is the effectiveness of the DRA, which depends on the DRA concentration.

Alternative approaches. Transfer function models for the PDE system eq. (10-12) are obtained by linearizing these equations and carrying out a Laplace transformation. The resulting transfer function is transcendent. Simple models of the pipeline in the form of a lumped parameter system can be obtained by a Taylor series expansion of transcendent transfer functions. The resulting algorithms are less time-consuming and hence better suited for critical real time applications [21]. Use of Neural Nets (NN) presents another possibility for system modeling using a black box approach: trained by field data, NN are able to describe the pipeline behavior without any knowledge about pipeline physics. NN are of special interest [22]

- for pipelines with complex physical behavior, where a physical description is time consuming (or maybe not possible to find), or
- as an addendum to conventional RTTM approaches according to eq. (10-12)

LDS using RTTM. Using and solving eq. (10-12) in real time, it is possible to eliminate transient effects introduced by

- fluid compressibility and pipe wall elasticity, and
- temperature dependence of the density.

Early proposals using RTTM for LDS purposes can be found in [23] and [24]. Corresponding LDS are called real time transient model (RTTM) systems, [2]. RTTM-LDS can also be used during transient pipeline operation, e.g. during start-up of a pipeline; this is especially useful for gas pipelines, where large compressibility results in severe transients. Two possibilities for using mathematical model information are given here:

Deviation analysis: Only three boundary conditions are required to drive the numerical solution algorithm, e.g. $p_I(t)$ and $p_O(t)$ for inlet and outlet and $\rho_I(t)$ (or $T_I(t)$) for inlet. If more measurements are available (e.g. flows $v_I(t)$ and $v_O(t)$ or additional pressure measurements along the pipeline), these measurements can be compared with the simulated values. If there is a significant deviation, leak alarm will be given.

Model Compensated Mass Balance: The RTTM can be used to calculate the line fill

$$M_L = \int_0^L \rho(x) A(x) dx\,. \tag{19}$$

according to eq. (2) in real-time. The imbalance subsequently can be compared with

$$R \begin{cases} < A & \Rightarrow & no\ leak \\ \geq A & \Rightarrow & leak \end{cases} \tag{20}$$

against a threshold A to evaluate the leak alarm.

4.3 Pressure/flow monitoring

Sudden leaks result in sudden changes of pressure and flow at inlet and outlet, respectively. Usually the pressure drops as a result of a leak.

Wave alert method. Applying pressure transducer along the pipeline, the negative pressure drop Δp can be observed as a wave propagating with wave speed a through the pipeline, downstream and upstream with respect to the point of the leak. Assuming isentropic flow without friction, the pressure wave amplitude is given by [14]

$$\Delta p = -\rho \cdot a \cdot \Delta v \tag{21}$$

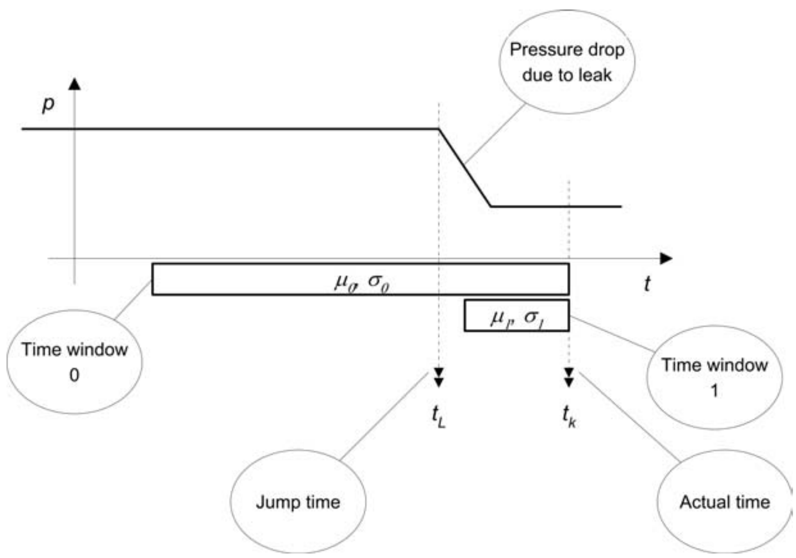
where ρ denotes fluid density and Δv describes the flow amplitude caused by a sudden leak. Leaks will be detected computing

$$\frac{dp}{dt} \approx \frac{\Delta p}{\Delta t} \begin{cases} \leq -A & \Rightarrow & no\ leak \\ > -A & \Rightarrow & leak \end{cases} . \tag{22}$$

The wave alert permits leak localization as shown below.

Pressure point analysis. The Pressure Point Analysis (PPA) [25] utilizes the pressure drop produced by a leak.

Figure 5: Pressure Point Analysis (PPA) principle. ©EFA Technologies, Inc., Sacramento (USA).



Two time windows

$$\begin{aligned} \mathbf{p}_0(k) &\equiv \left[p(k - N_0 + 1) \ldots p(k) \right] \\ \mathbf{p}_1(k) &\equiv \left[p(k - N_1 + 1) \ldots p(k) \right] \end{aligned} \tag{23}$$

with window length N_0 and N_1 define two populations, $N_0 > N_1$. $p(k)$ is the actual sampled pressure for discrete-valued time $k \equiv k \cdot T_0$ for sampling time T_0. Each population is assumed to be Gaussian distributed, $N(\mu_0;\sigma)$ and $N(\mu_1;\sigma)$;

$$\hat{\mu}_0(k) = \hat{\mu}_0(k-1) + \frac{p(k) - p(k - N_0 + 1)}{N_0}. \tag{24}$$

and

$$\hat{\mu}_1(k) = \hat{\mu}_1(k-1) + \frac{p(k) - p(k - N_1 + 1)}{N_1}. \tag{25}$$

provide estimates for unknown means μ_0 and μ_1, respectively. Pressure drop Δp is estimated using

$$\Delta\hat{p}(k) = \hat{\mu}_0(k) - \hat{\mu}_1(k). \tag{26}$$

Appropriate alarm thresholds α arise from the fact, that

$$t \equiv \frac{\Delta\hat{p}}{\sqrt{\frac{N_0 - N_1}{N_0 - 1}} \cdot \frac{\sigma}{\sqrt{N_1}}}. \tag{27}$$

is Student-t-distributed, as described in [25].

4.4 Statistical analysis

The degree of statistical involvement varies widely with the different methods in the API classification of internally based systems. In a previous section, we investigated the Pressure Point Analysis (PPA), which has been assigned to pressure/flow monitoring methods; an alternative assignment to statistical analysis methods would also be possible.

Another example is the LDS described in [26], basing on the Wald's Sequential Probability Ratio Test (SPRT). The imbalance

$$R(k) \equiv \dot{M}_I(k) - \dot{M}_O(k - \tau) \tag{28}$$

will be used and checked for two hypothesizes:

$$\begin{aligned} H_0:&\quad R(k) \propto N(\mu_0;\sigma) \\ H_1:&\quad R(k) \propto N(\mu_0 + \Delta\mu;\sigma) \end{aligned}. \tag{29}$$

Inlet mass flow $\dot{M}_I(k)$ and outlet mass flow $\dot{M}_O(k)$ are sampled, with discrete-valued time $k \equiv k \cdot T_0$ for sampling time T_0. The time shift $\tau \equiv \tau \cdot T_0$ considers the time for a (flow) wave needed to propagate with wave speed a through a pipeline with length L:

$$\tau = \frac{L}{a}. \tag{30}$$

Wald's SPRT results in a sequential computation of the likelihood ratio

$$\lambda = \ln\left(\frac{N(\mu_0 + \Delta\mu;\sigma)}{N(\mu_0;\sigma)}\right)$$
$$\lambda(k) = \lambda(k-1) + \frac{\Delta\mu}{\sigma^2}\left(R(k) - \mu_0 - \frac{\Delta\mu}{2}\right). \tag{31}$$

This variable will be compared with

$$\lambda \quad \begin{cases} < B & \Rightarrow \quad \textit{no leak} \\ \geq A & \Rightarrow \quad \textit{leak} \end{cases} \tag{32}$$

against two thresholds *A* and *B* with *A*>*B* to evaluate the leak alarm. No decision is made if $B \leq \lambda < A$. Mean μ_0 and standard deviation σ are not known; therefore estimates are required. A simple approach is to use running estimates like eq. (24), leading to a sequential generalized likelihood ratio test. It is also possible to use different pre-assigned values for σ according to the actual operating condition, e.g. during transient operation, hereby decreasing the false alarm probability at the expense of increasing the lowest detectable leak rate.

5 Leak Localization

5.1 Externally based LDS

Local leak sensors of externally based systems often provide very accurate leak localization at the expense of high system costs and complexity of installation.

5.2 Internally based LDS

From a statistical point of view, leak detection is a detection problem, whereas leak location (and rate determination) is an estimation problem: Given the field data, the location (and the rate) of the leak has to be established.

Gradient intersection method. For a simple horizontal pipeline of diameter *D* (and cross-sectional area *A*), steady state analysis basing on eq. (10-12) for pipelines transporting liquids with constant line density ρ_L yields

$$\frac{dp}{dx} = f\,\frac{\rho v|v|}{2D} = f\,\frac{\dot{M}\,|\dot{M}|}{2DA^2\rho_L} \tag{33}$$

for pressure drop per unit length dp/dx. *f* denotes the Darcy-Weisbach friction factor according to eq. (14) and (15) for turbulent and laminar flow, respectively. Pressure drops linearly if *f* and *D* are constant along the pipeline and in absence of a leak. If a leak of leak rate $\dot{M}_{leak}$ occurs at leak location x_{leak}, upstream pressure drop is given by[6]

[6] Unchanged mass flow of inlet had been assumed for simplicity but without loss for generality.

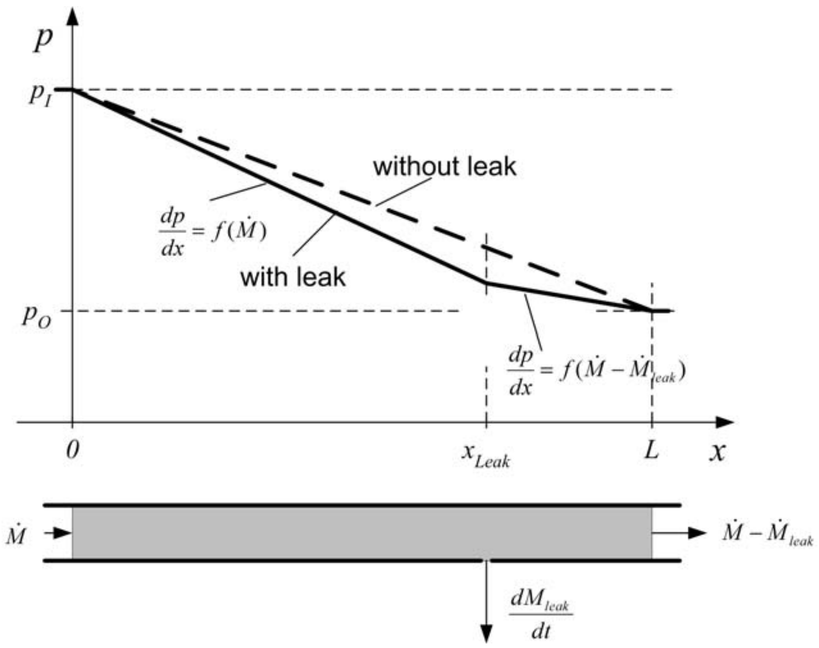
$$\frac{dp}{dx} = f\,\frac{\rho v|v|}{2D} = f\,\frac{\dot{M}\left|\dot{M}\right|}{2DA^2\rho}, \tag{34}$$

whereas downstream pressure drop decreases to

$$\frac{dp}{dx} = f\,\frac{\rho v|v|}{2D} = f\,\frac{\left(\dot{M} - \dot{M}_{leak}\right)\left|\left(\dot{M} - \dot{M}_{leak}\right)\right|}{2DA^2\rho}. \tag{35}$$

Eq. (34) and eq. (35) define two straight lines, which intersect at the leak location.

Figure 6: Leak localization with gradient intersection method.



Measuring the straight line gradients (assuming that the friction factor f is known and estimates of the leak rate $\dot{M}_{leak}$ are available) and calculation of the point of intersection therefore allow for leak location estimation [24].

Wave propagation analysis. If a sudden leak $\dot{M}_{leak}$ occurs at time t_{leak}, a negative pressure wave with wave front amplitude Δp can be observed propagating with wave speed a through the pipeline with cross-sectional area A, downstream and upstream with respect to the leak location x_{leak}. Applying eq. (21) yields[7]

$$\Delta p = -\rho \cdot a \cdot \Delta v = -\frac{1}{A} \cdot a \cdot \dot{M}_{leak}. \tag{36}$$

Using pressure transducers installed downstream and upstream of the leak location, this wave can be detected at time

[7] In real applications, the wave amplitude Δp decreases due to heat transfer and friction losses, leaving the basic principle untouched.

$$t_{up} = t_{leak} + \frac{x_{leak} - x_{up}}{a} \tag{37}$$

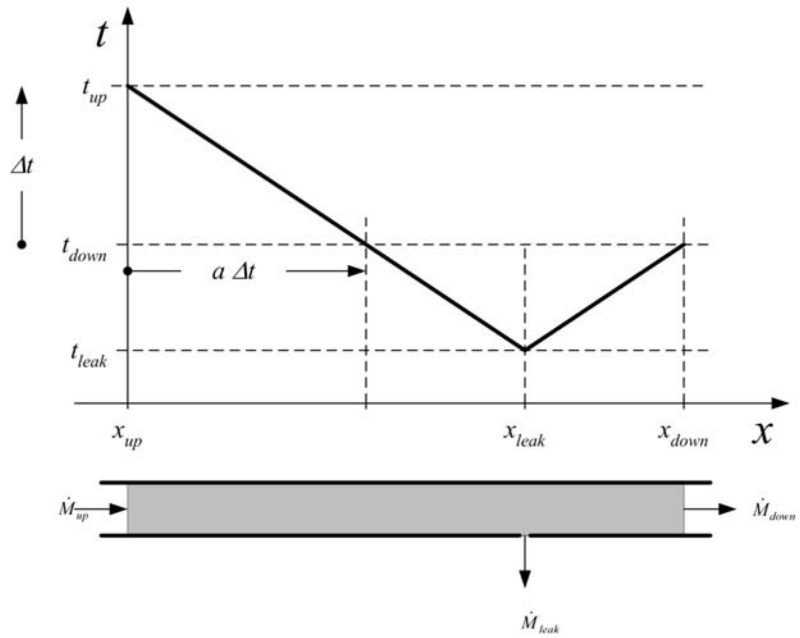
passing the pressure transducer upstream position x_{up} and

$$t_{down} = t_{leak} + \frac{x_{down} - x_{leak}}{a} \tag{38}$$

passing the pressure transducer downstream position x_{down}. The leak location then yields

$$x_{leak} = \frac{1}{2} \cdot \left(\left(x_{down} - x_{up}\right) + a \cdot \left(t_{up} - t_{down}\right)\right). \tag{39}$$

Figure 7: Leak localization with wave propagation analysis.



Time difference determination $\Delta t \equiv t_{up} - t_{down}$ (assuming pressure transducer locations are known) gives the leak location estimate.

Optimization methods. It is possible to extend the mathematical model eq. (10-12) with a leak described by leak rate $\dot{M}_{leak}$ at leak location x_{leak}. This can be used using a RTTM-based deviation analysis approach. If a leak occurs, simulated and measured values from redundant variables differ at the first moment. After leak detection, model parameters $\dot{M}_{leak}$ and x_{leak} will be tuned automatically using an optimization method, e.g as proposed by Levenberg and Marquard; goal of the optimization is to minimize the difference between measured and simulated variable. $\dot{M}_{leak}$ and x_{leak} correspond to the minimum of the difference.

Multiple hypothesis testing. If an extended mathematical model with model parameters $\dot{M}_{leak}$ and x_{leak} is available, multiple mathematical models can be computed in parallel. Each model corresponds to a specific hypothesis, associated to specific values of the model parameters $\dot{M}_{leak}$ and x_{leak}. Leak location estimation is equivalent with finding the best-matching mathematical model by means of a statistical hypothesis test.

6 An Extended RTTM Approach

The internally based LDS methodologies presented previously point up two different points of views:

- *Simulation point of view.* From this point of view, detecting a leak mainly requires the knowledge of the transient behavior of a pipeline, either without or with leak. Model compensated mass balance techniques are an example: Assuming that the mathematical model (e.g. eq. (10-12)) is correct, the computation of the corrected imbalance (residual) eq. (1) leads to the straightforward leak detection eq. (20); not much statistics are required.

  Exponents of this kind of thinking are able to include a-priori-knowledge of the pipeline in a very sophisticated way. But they tend to neglect the decision nature of leak detection: at the end, beside all sophisticated computations, there must be the simple binary decision: "no leak" or "leak".

- *Statistical point of view.* Statisticians strongly emphasize the decision aspect of leak detection: at the end, the LDS has automatically to decide if there is a leak or not. This leads to decision theory [30]. The LDS basing on Wald's Sequential Probability Ratio Test (SPRT) described in [26] and the Pressure Point Analysis PPA [25] are previously discussed examples: Assuming that process variables like uncompensated mass imbalance (SPRT) or pressure (PPA) behave in a statistical "good" manner[8], leak detection reduces to a statistical detection problem, solvable by well known statistical methods, e.g. multiple hypothesis testing.

  Exponents of this kind of thinking come to the point: leak detection is a decision problem, and they can apply well known statistical methods like SPRT. But they tend to neglect the process variables are not stationary at all, hereby reducing the possibility of include a-priori-knowledge.

In order to combine the advantages and eliminates the disadvantages of both points of view, the now presented *Extended* RTTM (E-RTTM) approach [24, 27, 28] combines both methodologies:

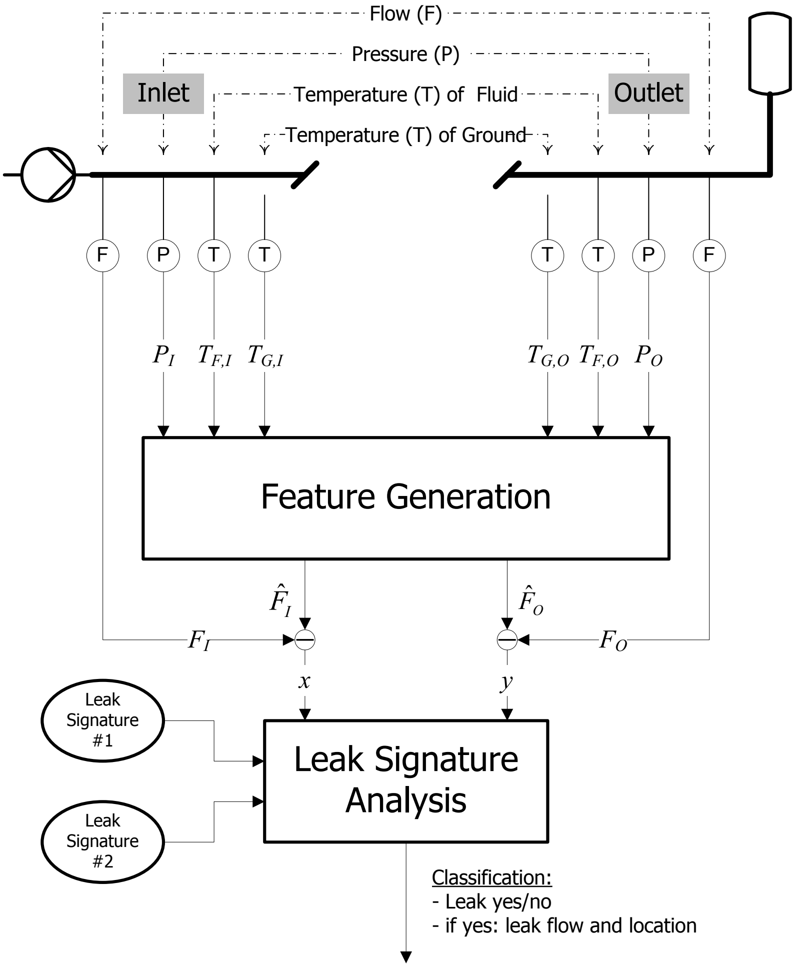
- A "classical" RTTM generates deviations between measured and estimated flow basing on the RTTM deviation analysis. This module will be called subsequently "feature generator" [24].

- A leak signature analyzer uses the deviations as input. It assigns the pipeline to one of two classes: class "no leak" and class "leak".

This forms an online pattern recognition scheme [29] with a feature generation module and a leak signature analysis module.

[8] Usually meaning stationary normal distributed process variables.

Figure 8: Extended RTTM-LDS.



Feature generation. This module computes deviations

$$x(t) \equiv v_I(t) - \hat{v}_I(t)$$
$$y(t) \equiv v_O(t) - \hat{v}_O(t) \tag{40}$$

with measured flow $v_I(t)$ and $v_O(t)$ at inlet an outlet, respectively[9]. $\hat{v}_I(t)$ and $\hat{v}_O(t)$ denote estimated flows at inlet and outlet, assuming that there is no leak.; calculation is computer based solving the PDE system eq. (10-12) for given boundary conditions. Up to that point, the extended LDS just is a RTTM LDS using the deviation principle as described before.

Leak signature analysis. The deviations are inputs to this next module, which uses them as features in the context of a pattern recognition scheme. Transient effects are compensated to some extend by the pipeline observer; so the classifier doesn't need to consider them. From a theoretical point of view, neglecting model errors and assuming appropriate measurement noise characteristics, the deviations are stationary normal distributed process variables. It is then straightforward to use well known statistical classification tools to perform leak detection; a rich set of them is available [29]. An appropriate technique is described in [30]: to perform leak detection, the deviation sequence will be analyzed to discover changes in the statis-

[9] Volume flow $\dot{V}$ and mass flow $\dot{M}$ could also be used instead of v; F in Fig. 8 therefore denotes one of these three variables.

tical model behavior. If a significant change of parameters describing the mathematical model will be detected, leak alarm is raised. Leak persistence is tested using a simple outlier removal algorithm: during a test phase, the leak test must steadily indicate a leak; otherwise, the leak alarm will be discarded.

Leak localization. The leak signature analysis additionally estimates leak location (and rate) using two methods described previously: gradient intersection method [25] and wave propagation analysis. The algorithm automatically uses the method best suited for the specific application and operation condition.

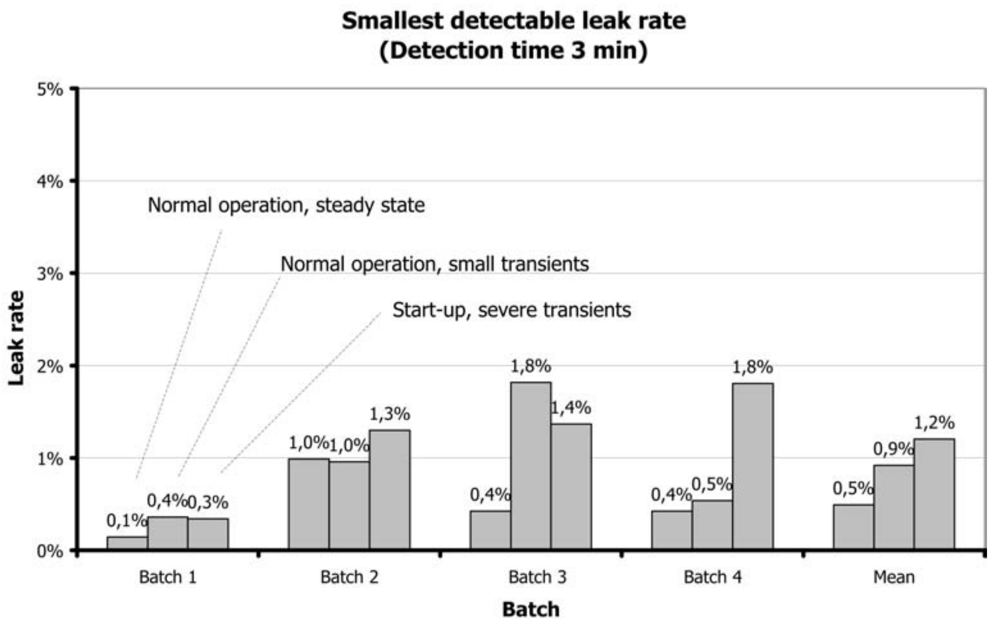
6.1 Field Test 1: Liquid Pipeline, Multi-Batch

The first application is a liquid pipeline, operated in multi-batch-mode with 7 different batches. E-RTTM applicability had been tested performing extensive tests including leak tests. Three different operating conditions were defined:

- *Normal operation, steady state.* The pipeline is pressurized with nominal pressures, nominal flow is present; we have (more of less) steady state.
- *Normal operation, small transients.* The pipeline is pressurized with nominal pressures, nominal flow is present. Controlling a valve behind the outlet area, small transients were generated.
- *Start-up, severe transients.* Staring the pumps, severe transients were generated.

Smallest detectable leak rate. The smallest detectable leak rate was determined using a statistical analysis [27]; it depends on operating condition and kind of batch.

Figure 9: Smallest detectable leak rate using E-RTTM (liquid application).

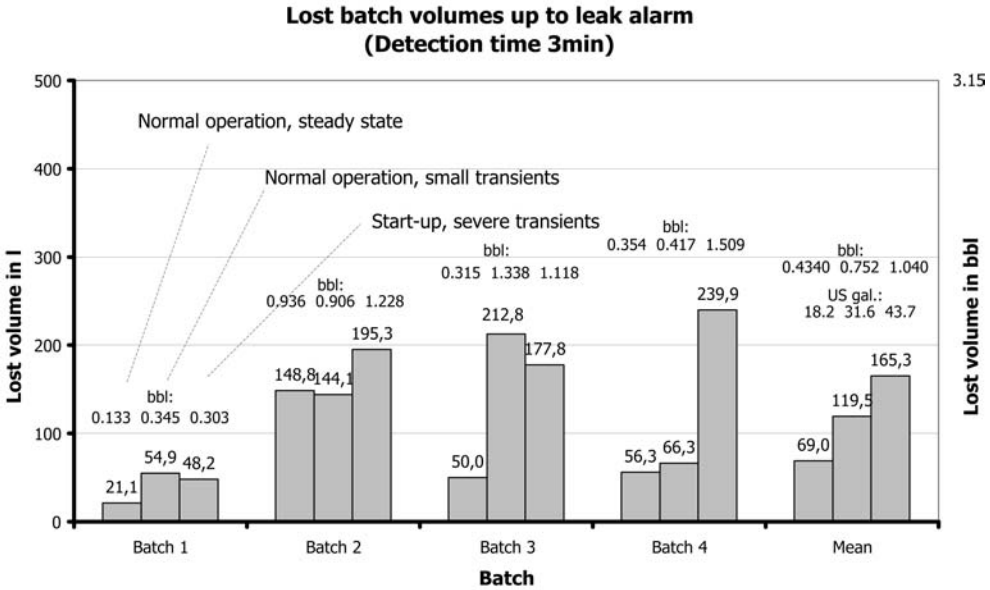


- If a leak occurs during normal operation, steady state, the mean for the smallest detectable leak rate is about 0.5%.
- If a leak occurs during normal operation with small transients, mean value increases to 0.9%

- If a leak occurs during start-up with severe transients, mean value increases to 1.2%.

Lost batch volume. The lost batch volume up to the leak alarm is a more comprehensive measure of environmental pollution.

Figure 10: Lost batch volume up to a leak alarm using E-RTTM (liquid application).



- If a leak occurs during normal operation, steady state, the mean value for the lost batch volume up to leak alarm is about 69l (0.434bbl, 18.2 US gal).
- If a leak occurs during normal operation with small transients, mean value increases to 120l (0.752bbl, 31.6 US gal).
- If a leak occurs during start-up with severe transients, mean value increases to 164l (1.040bbl, 43.7 US gal).

Accuracy of leak localization. Near the middle of the pipeline, a test quantity had been removed from the line; typical leak localization accuracy was about 1 to 2%.

Conclusion. The E-RTTM LDS according to Figure 8 has proven his applicability and very good performance for a liquid application, a multi-batch-pipeline transporting up to 7 different batches.

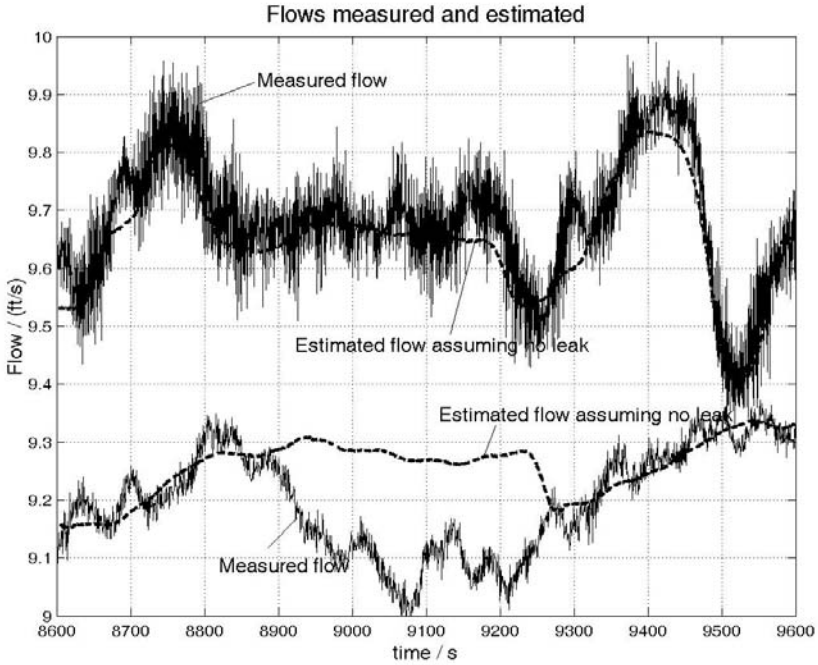
6.2 Field Test 2: Gas Pipeline

The second application [31] for testing the E-RTTM method is concerned with a gas pipeline. Gas is CO (carbon monoxide), which has in the present case nearly ideal gas properties; PVT equation (16) can therefore be used.

Leak tests. Leak tests had been accomplished by flaring gas at the inlet section. Three different kinds of leaks had been introduced: 0.5%, 1% and 2.5% with respect to the nominal flow at reference conditions 0°C, 1.013bar (32°F, 14.7psi).

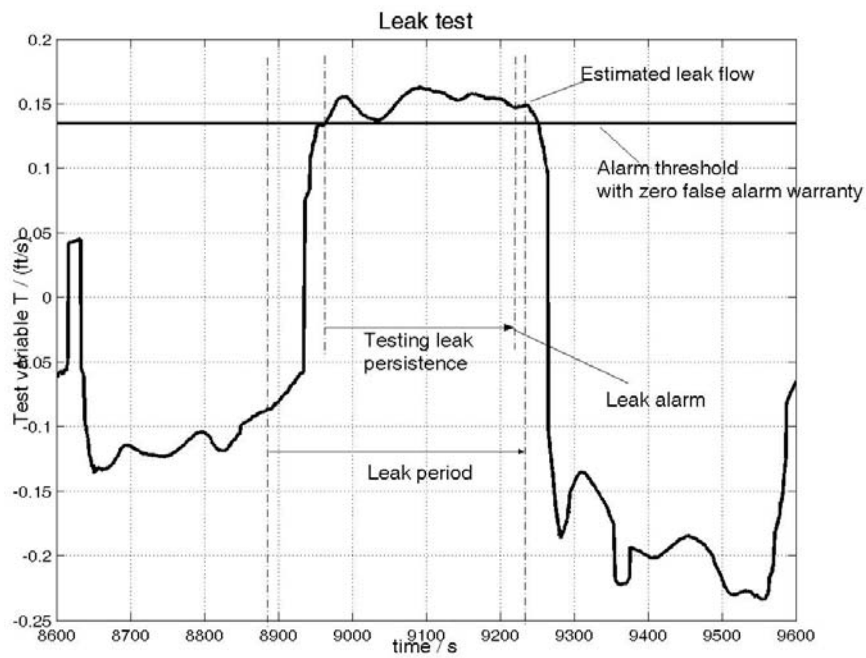
The next figure compares measured flows $v_I(t)$ and $v_O(t)$ and estimated flows $\hat{v}_I(t)$ and $\hat{v}_O(t)$ for inlet out let, respectively.

Figure 11: Measured and estimated flow using E-RTTM, leak rate 1% (gas application).



Due to the deviation principle, significant deviations between measured and estimated flow indicate a leak in the pipeline, which occurs for the application at time *t*=8900s. Results of the leak signature analysis are shown by the next figure.

Figure 12: Leak test using E-RTTM, leak rate 1% (gas application).



A test variable *T* is tested against an alarm threshold *A*. *T* exceeds *A* shortly after leak occurrence; now, testing leak persistence within the scope of outlier removal procedure starts. Leak alarm is raised after leak persistence has been confirmed.

Lost gas mass. Like for liquids, the lost gas mass up to the leak alarm is a more comprehensive measure of environmental pollution.

Table 1: Results using E-RTTM for gas pipeline.

Leak detection time	M_{Lost} (2.5% leak)	M_{Lost} (1 % leak)	M_{Lost} (0.5 % leak)
80s	2.84 kg (6.26 lb)	0.94 kg (2.07 lb)	0.66 kg (1.46 lb)
140s	4.97 kg (10.96 lb)	1.65 kg (3.64 lb)	1.16 kg (2.56 lb)
200s	7.11 kg (15.67 lb)	2.35 kg (5.18 lb)	1.65 kg (3.64 lb)
260s	9.24 kg (20.37 lb)	3.06 kg (6.75 lb)	2.15 kg (4.74 lb)
320s	**11.38 kg (25.09 lb)**	**3.76 kg (8.29 lb)**	**2.64 kg (5.82 lb)**
380s	13.51 kg (29.78 lb)	4.47 kg (9.86 lb)	3.14 kg (6.92 lb)
440s	15.64 kg (34.48 lb)	5.17 kg (11.40 lb)	3.64 kg (8.02 lb)

This table summarizes the results for different leak detection time parameters. Finally, leak detection time parameter had been chosen to 320s; corresponding lost gas masses are between 2.64kg (5.82lb) and 11.38kg (25.09).

Zero false alarm warranty. Alarm threshold *A* has been chosen to *A*=0.041m/s (0.135ft/s) to ensure no false alarm for the whole test time period of more then 4 months. Detection of leak according to Figure 8 is therefore possible without any false alarm.

Conclusion. The E-RTTM LDS according to Figure 8 has proven his applicability and very good performance for a gas application, a pipeline transporting carbon monoxide (CO).

7 Conclusions

This paper presented a survey about leak detection and localization methodologies, methods, techniques and systems. LDS were subdivided according to API 1130 2nd Ed. [2] into internally based and externally based systems; for both categories, examples had been presented.

Furthermore, an Extended RTTM approach was presented combining the advantages of RTTM LDS and statistically based LDS. The applicability of this method was proven for a liquid multi-batch pipeline and a gas pipeline.

The University of Applied Sciences in Gelsenkirchen and KROHNE Oil & Gas B.V. from the Netherlands (KOG) closely work together on the field of leak detection. The outstanding properties of the E-RTTM technology therefore motivates KOG to choose E-RTTM for **PipePatrol**, the KOG leak detection and localization system.

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Acknowledgements

The author thanks KROHNE Duisburg and KROHNE Oil and Gas B.V. Dordrecht for (not only financial) support and all staff members for their patience and enthusiasm.

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