A SURVEY ON THE STATE-OF-THE-TECHNIQUE ON SOFTWARE BASED PIPELINE LEAK DETECTION SYSTEMS

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Abstract. This paper describes a general technical survey on software based leak detection systems (LDS), approaching its main technological features, the operational situations where they are feasible, and the scenarios within the Brazilian pipeline network. The decision on what LDS to choose for a given pipeline is a matter of cost, suitability and feasibility. A simpler low cost, less effective product, but with a fast installation and tuning procedure, may be more suitable for a given operational site (pipeline configuration, kind of fluid, quality of instrumentation and communication), than a complex, high cost, efficient product, but taking a long time to be properly installed. Some other may really have a level of complexity that will require a more sophisticated system. A few number of them will simply not be suitable to have a LDS: it may be caused by the poor quality or absence of instrumentation, or, the worst case, due to the lack of technology to approach that specific case, e. g., multiphase flow lines, or those lines that commonly operates in slack condition. It is intended to approach here the general state-of-the-technique and make some initial comments on the costs.

Key Words: Leakage, Leak Detection, Pipeline Simulation, Flow Measurement, and SCADA

1 INTRODUCTION

Leak detection for the petroleum industry plays a key role within the companies. Usually, it is common for those companies to have a well established pipeline leakage risk assessment matrix. It considers the pipelines proximity to potential areas of damage, such as beaches, rivers, and metropolitan areas. Within the Brazilian pipeline network, a relevant percent of them are about to reach their projected life span, being, this way, more likely to face leakage's. The decision of installing LDS in a given line is based on the following benefits: to prevent/minimize production loss; to prevent/minimize costs of recovering damages to the environment and to communities caused by petroleum leakage; to ensure that the company have good documented technical data, in a way to face legal matters related to leakage's, and, to preserve the company's general image.

2 FLUIDS AND PHASES TO CONSIDER

Ideally, one should be able to detect leaks for all fluids at all states or phases. Unfortunately, not all of them are suitable to be under a LDS. For example, there is no reliable technology, to detect leaks for multiphase flow. The same can be said about the wet natural gas and any liquid under slack condition. Some comments follows according to the different fluids.

2.1 Batches of different crudes

One consider a crude, an oil with no dissolved gas. The nature of the crudes may differ, and its not rare the situation where one have a given type of crude pushing another totally different one. Even on this situation, one have to be able to prevent and detect leakage's. Some crudes may have a slight non-Newtonian behavior, like those coming from Marlim field, at Campos Basin, Brazil. Some other may show a high viscosity, turning compulsory its pre-heating to allow it to flow.

2.2 Batches of different liquid refined products

Those refined products ranges from the liquefied petroleum gases (LPG), like ethane, propane, butane and ethylene, going through pentanes, gasoline's and naftas, up to jet fuels (kerosene's), and diesels. The LPG's requires a more closer control on the entire pipeline pressure, once they can turn to the gas phase during their transportation, especially at the higher points of the line. It would feature the slack condition, to which there's no known leak detection technology available.

2.3 Gases

Natural gas pipelines are sometimes the most attractive pipelines under the business point of view. They are usually linked to power generating plants and chemical industries, among others, that practically turns an eventual operation interruption, to a chaotic situation, especially to those industrial locations closer to the pipeline. However, due to high compressibility, and usually high spacing between measurements, Leak Detection at gas pipelines are not fully believed to be realistic. Some another effects may also take place, such as the liquefying effect when the natural gas carries some heavier fractions, and the flow pressure increases; it usually let a small fraction to turn to the liquid state, and the flow properties simulation becomes erratic.

2.4 Emulsions (liquid two phase flow)

As the oil fields are being depleted, they start to produce water, which mixes with the oil. So, the majority of those mixtures behaves as a non-Newtonian fluid. In a practical sense, it means that most of the conventional equations as well as some measurement procedures will not work anymore. New kernels must be developed to ensure compliance with this reality.

2.5 Binary liquid-gas mixtures (Gas Liquid two phase flow)

This is one of the big challenges within the leak detection industry. Two very different flow rates, for two mixable or not fluids in different phases. No model based software is enough to treat this situation. Some attempts has been made using statistical software, for very constrained and controlled situations.

3 OPERATIONAL CONDITIONS

The LDS must be able to operate even in a non optimal performance, for all the operational conditions. At the static or stationary condition, also called "Shut in", it must be able to detect under the situation of zero flow. The transient pump startup is the situation where most the leakage's take place. During the steady state, some leakage's may happen due to structural problems like uncompensated thermal fatigue. Finally, at the transient pump shutdown, is the most uncommon condition to face leak, even though it is possible. Special attention must be taken, when the line goes to the slack flow state, because, at that condition, no Leak Detection function can be ensured.

The kind of pipeline is also important, because it will regulate the sort of difficulties one would face, for installing, tuning and evaluating LDS. Onshore rigid pipelines are the most common, and usually those easier to install. Offshore rigid pipelines shows the constraint of not allow to have intermediate instruments, since it is quite difficult to send data in real time from water. Offshore Flexible lines basically shows the same difficult of the offshore rigid ones.

4 STATE OF THE TECHNIQUE

Consider Figure 1, where we have a schematic of a general software based LDS, or a Model based LDS, as it was initially called, according to the API 1130 (1995), Nicholas et Alli (1992) and Loupa (1993). The main concepts will appear underlined. The Model based solution compares estimated and measured data. In a given monitored pipeline segment, meters are installed, upstream and downstream to the segment. Those are meters of volumetric flow rate Q (usually the most important), pressure P, temperature T and density ρ (Figure 1, shows just flow and pressure meters, as an example). They are able to send the information in a digital format to a SCADA, or any other Data Acquisition System. Within the Figure 1, μ terms for the dynamic viscosity, D is the pipeline internal diameter, and e1 and e2 are arbitrary values of differences. The way the SCADA acquires field data features the Real Time Data Acquisition Algorithm. The two most common ways to do so, are polling and acquisition by exception.

4.1 LDS Concepts

In Figure 1, once knowing the variables P and Q, acquired at one of the problem boundaries (e. g., at the inlet), it is possible to estimate the value of the same variables at the other boundary. The calculations is performed by a software piece called State

Estimator. The State Estimator takes into consideration the involved physical concepts. The estimated variables are assigned with a quote ('), in Figure 1. With both estimated and measured (acquired) variables, the comparison is performed. Every LDS has it's own way to evaluate this difference, and then decide whether there is or not a leak. This way of analyze this difference is usually a computational algorithm (not necessarily, I mean, it may be an heuristic approach), called Leak Detection Algorithm. The Leak Detection Algorithm establishes an Alarm System according to the difference between measured and estimated data, as well as based in other information that come from SCADA System, such as, instrument failure, for example.

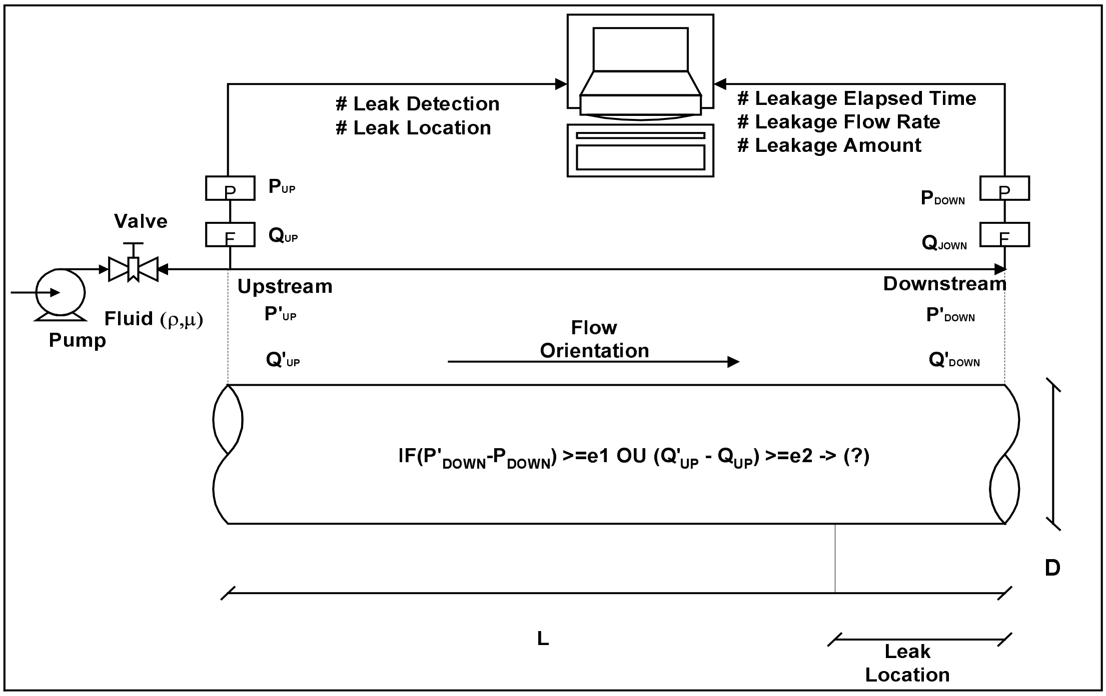

Figure 1 - Schematic of a LDS

Even with a good physical model used by the State Estimator, some significant differences between measured and estimated property usually take place, at the normal operational condition, i. e., without a leakage. This is due to the presence of non-deterministic (probabilistic or stochastic) variables in the calculations of the estimated property. Those variables come from the pipeline (roughness, actual internal diameter, valve constants – specially the old ones, etc.) as well as from the surroundings of the pipeline (soil and/or water), i. e., their thermal properties, specially, average temperature and thermal conductivity. Thus, it is necessary a Tuning Procedure for those variables, which is done by using the measured property, as a function of the estimated property at the normal operational condition (i. e., without leakage). Thus, a statistical fit is performed in order to have the estimated property equal to the measured one, using as statistical parameters, the so called Tuning Variables (roughness, internal diameter, etc.). This fit is quite dynamic, i. e., it has to be performed periodically.

Finally, with the exception of PPA (Pressure Point Analysis) technology (Farmer, 1993), and the LDS's based on acoustic sign analysis (which is not model based) most solutions is strong and directly dependant on the flow measurement, i. e., the best the flow measurement is, the best will be the leak detection performance.

4.2 State Estimators

There are many ways to perform leak detection, i. e., some solely based on instruments/hardware, others using pieces of software to perform volume imbalance calculations. As a first way to classify the methods, we will consider two approaches: the Real Time Model (RTM), which encompasses the "Compensated Volume Balance" (CVB), from Nicholas et Alli (1992), and the RTTM (Real Time Transient Model).

CVB approaches material balance in order to compute the variations of Linefill i (some literature can also call it Linepack but once it may include batches, we preferred here this term), which is the pipeline internal amount of mass, expressed in terms of volume, and its impact on the flow imbalance. Basically, they focus their analysis according to the equation 1.

$$Q_{in} - Q_{out} = \frac{\Delta i}{\Delta t} \pm \Delta Q \qquad (1)$$

where Δt is the time difference between two SCADA cycles, ΔQ is the flow rate accuracy, and the indexes in and out terms for the pipeline inlet and outlet respectively.

They divide the monitored segment into n small pieces, called elements of discretization, and perform corrections for ρ at the middle of the element, as a function of T (the most sensible variable) and P, i. e., for the generic element k within the pipeline mesh, $\rho_k=\rho_k$ (P_k, T_k). They also estimates corrections for the element axial and radial expansion, as a function of P_k and T_k. Finally, the Linefill i_{total} will be the sum of the corrected volumes of all elements, i. e., i_{total}=sum(i_k). Note that it currently approaches batches, where one has to inform the initial batch position. API 1149 (1993) suggests the equations (2) to (8), and Tables (1) and (2), below, as examples of such corrections:

$$i_k = A_0 L_0 \rho_k (P_k, T_k) \qquad (2)$$

where A_0 is the cross sectional surface, and L_0 the the pipeline length, both at standard intial conditions.

$$\rho_k = (C_T)_k (C_P)_k \rho_0 \{[\exp(\frac{DP_k}{Ee}[1-\mu^2]) + 2\alpha \Delta T_k]\}[(1+\alpha \Delta T_k)] \qquad (3)$$

where C_T is the liquid volume correction factor for temperature, C_P the liquid volume correction factor for pressure, e the pipeline wall thickness, E the modulus of elasticity of pipe wall material, *f* the Darcy-Weisbach friction factor, μ the Poisson's modulus of pipe wall material, α the thermal expansion coefficient of pipe wall material and F the fluid compressibility factor.

$$(C_T)_k = \exp[-(\alpha_T)_k \Delta T_k (1 + 0.8(\alpha_T)_k \Delta T_k)] \qquad (4)$$

where $$(\alpha_T)_k = \frac{K_0 + K_1 \rho_0^{\beta}}{\rho_0^2} \qquad (5)$$

and the values for the constants K_0, K_1 and β are:

Table 1 - Constants for α_T calculations

Product	**K_0**	**K_1**	β
Crude Oil	613,9723	0	1
Gasoline	346,4228	0,4388	1
Jet Gasoline	2680,3302	-0,003363	2
Jet Kerosene	594,5418	0	1
Fuel Oils	186,9696	0,4862	1

$$(C_P)_k = \frac{1}{1 - F_k P_k} \tag{6}$$

where $$F_k = \frac{1}{(K_B)_k} = \frac{1}{10^6}\exp(A + BT_k + \frac{C}{\rho_0^2} + \frac{DT_k}{\rho_0^2})(1 - 7.30x10^{-6} P_k) \tag{7}$$

and the values of the constants A, B, C and D are:

Table 2 - Constants for F calculations

A	B	C	D
-1,6208	0,00021592	0,87096	0,0042092

And finally:

$$i_{total} = \sum_{k=1}^{n} i_k \tag{8}$$

Thus, $$\frac{\Delta i}{\Delta t} = \frac{i_{total}(t + \Delta t) - i_{total}(t)}{\Delta t} \tag{9}$$

where Δt minimum is the SCADA scan rate. Although based on the steady state assumptions, CVB can be used on some transient situations, like pump startup, using techniques like, for example, time filtering, based on concepts obtained from the control process theory (Fourier analysis, or exponential filters). They will be, however, less accurate than the RTTM.

On the other hand, there is the RTTM approach, which is far more complex, commonly requiring a powerful CPU, and performing a coupled differential balance of mass (equation of continuity), linear momentum (Euler's equation, equation of motion or Newton's second law, they are all the same within this context), and, in some cases, typically those involving gases, energy (equation of energy, or thermodynamics first law).

Equations (10) to (12) show the differential balance, expressed at first, according to it's fundamental formulation, and in terms of pressure and temperature thereafter, in formulations obtained from Liou (1983).

Mass Balance: The continuity equation.

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho U) = 0 \quad \text{or} \quad \frac{DP}{Dt} + \rho a^2 \frac{\partial U}{\partial x} = 0 \tag{10}$$

where a is the acoustic wave speed, U is the axial velocity, t is the time and x the pipeline axial dimension.

Linear Momentum Balance: the equation of motion. This is the main differential equation which is really integrated. It comes from a simplified form of the Navier Stokes equation. Within this context it is exactly the Newton's second law.

$$\frac{\partial}{\partial t}(\rho U) + \nabla \, . \, (\rho U \, . \, U) = \rho g + \nabla . \tau \quad \text{or} \quad \rho \frac{DU}{Dt} + \frac{\partial P}{\partial x} + \rho f \frac{U|U|}{2D} + \rho g \sin(\theta) = 0 \quad (11)$$

Energy Balance**:** the equation of energy, or thermodynamics first law.

$$\rho c_p \frac{\partial T}{\partial t} = (\nabla \, . \, k \nabla T) - \left(\frac{\partial \ln \rho}{\partial \ln T} \right)_p \frac{Dp}{Dt} + \Phi \text{ or}$$

$$\left(\frac{\partial H}{\partial P} - \frac{1}{\rho}\right)\frac{DP}{Dt} + \left(\frac{c_w}{\rho A} + c_p\right)\frac{DT}{Dt} = 4K_H \frac{(T_G - T)}{\rho D} + f\frac{|U|^3}{2D} \quad (12)$$

where c_p is the specific heat at constant pressure, c_w the thermal capacitance of pipe material per linear length, h the specific enthalpy, and K_H the heat transfer coefficient per linear length;

The same corrections performed to density, with respect to the temperature are performed within the RTTM. The advantage of RTTM, when compared to the RTM, is the results obtained during the transient flow, typically, pumping startup and shutdown. The RTTM results are more reliable, easier to identify, and allows to find leaks faster than the other, specially at long pipeline segments, which is the actual condition of most pipelines. On the other hand, it requires a complex numerical solution, usually based on the Method of Characteristics or Implicit Finite Differences. RTTM also requires a complex and long tuning procedure. As a counter-example, it is not necessary to tune pipeline internal roughness at the CVB approach. In order to compare both approaches, Table (3) brings the flow perturbations that may be caught by each one.

4.3 Leak Detection Algorithms (Some comments)

This is the issue where are the major differences among the products in the market. There is vast set of different approaches. Some suppliers offers a technology that attempts to statistically model pressure or flow behaviors (drops), and, from this approach provide a leak decision, via a set of choices (the algorithmic approach) or a set of inferences (the heuristic approach).

Table 3 - Flow perturbations and the related approaches

#	**Flow Perturbation**	**Approach**
1	Valve opening at Pumping startup	RTTM
2	Pumping stabilization	RTTM
3	Batch Interface Moving	RTTM/CVB
4	Batch Interface Growing	RTTM
5	Sonic Pressure Transience	RTTM/CVB(*)
6	Natural Transience	RTTM
7	Enabling a deliver	RTTM/CVB
8	Transience due to that deliver	RTTM
9	"Slack Flow"	None

(*) – It just allows the interpretation

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Some other bring a friendly MMI (Man Machine Interface), fully configurable, where there are plots which attempts to feature a flow condition or behavior (they are called "Signature Plots"). They are graphical displays of certain variables behavior (e. g. flow imbalance, and Linefill variation), at some well known situations (among them, the leak situation, but some other like slack flow, meter bias, transient packing, etc). Once given the signature plots, all the leak decisions are on the control room operator hands, who will analyze the plot evolution in real time, with the help of an alarm system. It is a graphical approach of the previous presented statistical scheme, with the advantage of being promptly realizable (the critical situation can be identified in the beginning of the plot drawing). Those two previous examples, rely on their State Estimator, to produce the data to be displayed or statistically analyzed.

As mentioned before, there are products that mixes the State Estimator with the Leak Detection Algorithm; they prefer to work directly with statistical distribution of flow behavior, relying on the statistical parameters such as variances, averages and accumulation percents, applied directly over the acquired data, to provide their decision about the existence of a leak. In this case, the tuning procedure will be considerable longer, in order to establish a database of behaviors, designed and built for each pipeline.

4.5 LDS Performance Parameters

Follow below a brief description of the main LDS performance parameters, obtained from API 1155 (1995).

The ability of o given LDS to inform correct decisions about the existence of a leak, is quite important, because, for most of the products, there is a number of false alarms. A false alarm has a huge cost, because it usually let the operator to shutdown the pumping. This ability, is called <u>Reliability</u>.

Besides, a LDS must be able to detect a leak, in the shortest time possible. In order to show this feature, for a given set of (LDS, pipeline, product), there is a curve that plots the leakage flow rate versus the detection time (also called response time). This curve is called Sensitivity Curve, or simply <u>Sensitivity</u>. It looks mostly like an hyperbole, in the sense that, short leak detection times will just catch big leaks, and the opposite, short leaks will require a longer time to be detected. Such curve depends on a series of factors, being the main ones, the flow rate meter accuracy, the type of fluid (for example, LPG will have a different curve than Diesel, at the same pipeline, using the same LDS, because they have different Linefill variations), the pipeline length and diameter (it will cause different transients), and the scan rate of the communication facilities.

An important task of a LDS is to quantify the leakage, after the detection. It usually includes the leakage time, flow rate, location and amount. An important performance parameter is the <u>Accuracy</u> of those values. It is important to realize that this is a general system accuracy, i. e., it is not the accuracy of a given instrument.

Usually, the Leak Detection Algorithm compares flow rate or pressure at the boundaries. If the State Estimator uses the transient approach, it will be able to compare a flow rate at one boundary to a pressure at the other. Thus, some LDS may have more options of comparison, than others. This is specially useful, when an instrument or a function becomes unavailable. In another words, the number of channels of comparison will measure the ability of continuing work (even in a degraded way) without a given instrument or function. This ability is called Robustness. Back to the Figure 1, the maximum number of channels is four: P x P', Q x Q', Q x P' and Q'x P. But, since CVB relies totally on the flow rate measurements, only RTTM will have a robustness of 4.

There are some other important performance factors, but they are related to the pipeline itself, not to the LDS. They include the number of instruments installed along the pipeline, the consistent distance between them, their performance parameters as an instrument (accuracy, repeatability, etc), their calibration status. A reliable, consistent and easily connectable SCADA system is also deterministic of good results.

5 DISCUSSIONS

At the real operation, LDS usually show some well known problems. We will try to approach them as follows:

5.1 High Compressibility

High compressible fluids such as liquefied gases, or even natural gases takes so long to accommodate within the pipeline, during a compressor or pump startup. It will generate delayed sonic transients, which are difficult to catch. Besides, it usually requires spacing between measurements, specially, flow rate measurements. It is one of the most critical variables for the LDS sensitivity.

5.2 Spacing between measurements

This constraint comes from the real way a pipeline can be constructed. It is not feasible to put instruments at every 15 km, for example. Real pipelines, have instruments between every 150 km, in some cases. This is to long, for a desired fast leak detection function. This will cause the transients to be long, as well.

5.3 Interfacing with SCADA systems

Most SCADA Systems has a proprietary way to store the LDS necessary real time information. This is a matter of selling more technology and services. Usually the SCADA manufacturer produces a communication driver that will allow to recovery those information, in real time. The problem is the cost, i. e., those drivers are very expensive, and usually they are a quite simple piece of software to have that high price. Some new SCADA manufacturers are now coming with a common protocol, and selling it as a part of the general package, what should have happened since the first SCADA.

5.4 Slack Condition

Although prohibited by most of the company's internal operational procedures, and by law at some places, the slack flow condition is very common to the operational reality. It happens when at given pipeline point, the pressure drops to a value lower than the fluids vapor pressure. It causes the fluid to turn to the gas state. From that point on, it is not possible to simulate the pipeline, and have the leak detection.

6 CONCLUSIONS

A LDS is a complex piece of software. It is a mix of different scientific areas, as well as a technological product. Thinking of LDS means to think in a set of pieces of software, always as a set, i. e., there's no LDS if one of those pieces weren't available. Besides we must know how to let them communicate among them, to describe them using a common language, and to estimate their performance in given scenario.

A LDS always come after the instrumentation, their validation and centralization under a SCADA system. It is premature to look for a LDS without a reliable instrumentantion under a SCADA system.

Not all operational pipelines are suitable to have LDS. The kind of flow, fluid, instrumentation, and communication facilities will be the key issues to define that suitability. But a significant percent of them may have a LDS installed.

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