DECIDING BETWEEN COMPENSATED VOLUME BALANCE AND REAL TIME TRANSIENT MODELS FOR PIPELINE LEAK DETECTION SYSTEM

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Abstract. This paper describes a technical procedure to assess a software based leak detection system (LDS), by deciding between a simpler low cost, less efective product, having a fast installation and tuning, and a complex one with high cost and efficiency, which however takes a long time to be properly installed. This is a common decision among the pipeline operating companies, considering that the majority of the lines are short, with single phase liquid flow (which may include batches), basic communication system and instrumentation. Service companies offer realistic solutions for liquid flow, but usually designed to big pipeline networks, flowing multiple batches and allowing multiple fluid entrances and deliveries. Those solutions are sometimes impractical to short pipelines, due to its high cost, as well as long tuning procedures, complex instrumentation, communication and computer requirements. It is intended to approach here the best solution according to its cost. In a practical sense, it means to differentiate the various LDS techniques. Those tecniques are available in a considerable number, and they are still spreading, according to the different scenarios. However, two most known and worldwide implemented tecniques hold the majority of the market: the Compensated Volume Balance (CVB), which is less accurated, reliable and robust, but cheaper, simpler and faster to install, and the Real Time Transient Model (RTTM), which is very reliable, accurated and robust, but expensive and complex. This work will describe a way to define wheter one can use or not a CVB in a pipeline.

Key Words: Leakage, Leak Detection, CVB, RTTM, Pipeline Simulation, Sensitivity

1 INTRODUCTION

Usually, the most important pipelines within a company, with regard to environmental damage potencial, are the short ones, according to the company´s pipeline leakage risk assessment matrix. This is due to the fact that they are often closer to potential areas of damage, such as beaches, rivers, metropolitan areas, indian lands, etc. As an example, for this paper one will consider as a short pipeline a line with no slack flow, basic instrumentation (pressure, flow rate, and sometimes density and temperature, at the inlet and outlet of the monitored pipeline segment), a central real time data acquisition system (which may be or not a SCADA system), and with the upper limits of length and diameter respectively set as 100 km and 16 in (0,4064 m), as it is in Baptista (2000).

A question comes: who can ensure that those lines will be protected by a specific tecnique of leak detection? A set of variables that will be important to this answer can be pointed out, like the reason between length and diameter, the minimum distance between measurements, the kind of fluid, and the communication scan rate. But how can one answer this question with a more technical approach.

Those lines are the major part of the entire Brazilian pipeline network, and a relevant percent are close to the projected life span, being, this way, more likely to face leakages. The decision of installing LDS in those lines were taken based on the following benefits: to prevent/minimize production loss; to prevent/minimize costs of recovering the environment due to damage caused by petroleum leakage; to let the company have good documented technical data, in a way to face prosecutions related to leakage's, and, to preserve the company´s general image. An additional issue that is now coming as a reality, is the fact that some environmental organisms (e. g., the California state) are trying to turn LDS compulsory for new pipelines.

2 DESCRIBING THE TWO OPTIONS

The "model" based solution compares estimated and measured data. It is also called Computational Pipeline Monitoring, according to API 1130 (1995). In a given monitored pipeline segment, meters are installed, upstream and downstream to the segment. Usually, one may have volumetric or mass flow rate (usually the most important), pressure, temperature and density meters. They are able to send the information in a digital format to a SCADA, or any other data acquisition system.

Taking the assumption that we know the variables pressure and flow rate, acquired at one of the problem boundaries, it is possible to estimate the value of the same variable at the other boundary. This calculations is performed by a software piece called State Estimator. The State Estimator accounts for the involved physical concepts. With both estimated and measured (acquired) variables, the comparison is performed. Proprietary products have their own way to evaluate this difference, and then decide whether there is or not a leak.

In a actual pipeline, even with a good and realistic 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 variables in the calculations of the estimated property. Those variables come from the pipeline (roughness, actual internal diameter, and others) 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 the tuning variables as the statistical parameters.

2.1 The Compensated Volume Balance - CVB

Some authors (Nicholas et Alli, 1992, Furness & Van Reet, 1986, Liou, 1994 and Furness, 1985) as well as some institutions (API #1155, 1995 and API #1130, 1995) have gone through a first attempt to classify the LDS technologies. The two most important are the Real Time Model (RTM), which encompasses the “Compensated Volume Balance” (CVB), and the RTTM (Real Time Transient Model).

CVB approaches material balance in order to compute the variations of linefill (a concept that terms for the total mass within the pipeline segment - LF), and its impact on the flow rate imbalance (Loupa, 1993, and Nicholas, 1992). It is assumed steady state conditions. There´s a unique equation that will base all the analysis, the equation 1, as follows.

$$Q_{in} - Q_{out} = \frac{\Delta LF}{\Delta t} \pm \Delta Q \tag{1}$$

where Q is the flow rate, and LF terms for the linefill.

They divide the monitored segment into small pieces, called elements of discretization, and perform corrections for fluid density (or volume) at the middle of the element, as a function of temperature (the most sensible variable) and pressure, i. e., for the generic element k, $\rho_k = \rho_k$ (P_k, T_k). They also estimates corrections for the element axial and radial expansion, as a function of temperature and pressure. Finally, the linefill will be the sum of the corrected volumes of all elements, LF_{total}=sum(LF_k). Note that this may approach batches of fluids, where one has to inform the initial batch position. Equations (2) and (3) generically describe this approach.

$$LF_k = A_0 L_0 \rho_k (P_k, T_k) \tag{2}$$

This basically describes a state equation, for liquids and gases, plus the corrections for radial and axial expansion due to pressure and temperature.

$$LF_{total} = \sum_{k=1}^{n} LF_k \tag{3}$$

Thus,

$$\frac{\Delta LF}{\Delta t} = \frac{LF_{total}(t+\Delta t) - LF_{total}(t)}{\Delta t} \quad (4)$$

where Δt minimum is the SCADA scan rate.

Although based on steady state assumptions, CVB can be used on some transient situations, like pump startup, using techniques like, for example, time filtering, based on concepts from the control process theory (Fourier analisys, or exponential filters, as sugested in Parry et alli, 1992). They will be, however, less accurate than the RTTM.

2.2 The Real Time Transient Model - RTTM

On the other hand, there is the RTTM approach. It is considerable more complex, requires a powerful CPU and computer resources as a whole. It performs a coupled differential balance of mass (equation of continuity), linear momentum (equation of motion or Newton's second law), and, in some cases, typically those involving gases, energy (equation of energy, or thermodynamics first law).

Equations (5) to (10) show the differential balance, expressed at first, according to it's fundamental form, and in terms of pressure and flow velocity (measurable variables), obtained from Liou (1983). This paper doesn't aims to go through the way to solve the EDP generated system but just to show and comment on it. Solutions are found on Liou, 1993, Bacon, 1986 and Liou & Tian, 1995.

Mass Balance: The continuity equation.

$$\frac{DP}{Dt} + \rho a^2 \frac{\partial U}{\partial x} = 0 \quad (5)$$

where a is the accoustic wave speed, and U is the flow velocity (unidimensional).

Linear Momentum Balance: the equation of motion.

$$\rho \frac{DU}{Dt} + \frac{\partial P}{\partial x} + \rho f \frac{U|U|}{2D} + \rho g \sin(\theta) = 0 \quad (6)$$

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

$$(\frac{\partial H}{\partial P} - \frac{1}{\rho})\frac{DP}{Dt} + (\frac{c_w}{\rho A} + c_p)\frac{DT}{Dt} = 4K_H \frac{(T_G - T)}{\rho D} + f\frac{|U|^3}{2D} \quad (7)$$

where cp is the specific heat at constant pressure, cw the thermal capacitance of pipe material per linear length, T_G is the ambient surrounding temperature, K_H the heat transfer coefficient per linear length, and H the specific enthalpy.

The advantage of RTTM, when compared to the CVB, is its better performance on the transient flow, specially, 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 measurements spacing. On the other hand, it requires a complex numerical solution, and a complex and long tuning procedure.

2.3 The way to detect leakages

There is a set of different techniques to detect a leak. 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), as suggested in Farmer, 1993.

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 statiscally analyzed.

3 THE WAY TO SELECT

To choose between CVB and RTTM, we will have to analyse the performance of the CVB software for each pipeline separately, for each fluid and alignement (a case), within the transient conditions (a scenario). Actually, the task to be performed includes the “ emulation” of what would be the expected data coming from a SCADA system for that line.

Most of LDS´s allows you to work offline, which means it provides a piece of software that allows it to receive data from a previously generated file, and treat those data as they were in real time. This will allow us to estimate the sensitivity of a given LDS scenario, for that particular CVB software. To generate those data, it is necessary to use one or more offline pipeline (commercial or not) simulators. For each pipeline, it will be necessary to generate one configuration file, and some cases/scenarios files. To do so, the pipeline simulation team, must be working in a very coordinate way with the LDS personnel. In a way to consider the flow rate uncertainties, one may introduce noise to the flow signal generated by the simulators, using a piece of software that randomnly generates error for a given percent. The same can be done for pressure and temperature, but those are less important.

Based on the assumption that the sensitivity curve will fit an equilateral hyperbole, the product (% flow leak) times (time of response) will aproximately be constant, which gives you the actual amount of leakage, until its detection. In other words, after this work, one can estimate the Teoretical Amount of Leakage (TAL), a case/scenario would have, until the leak detection.

At this point, a question take place: what would be a reasonable amount of fluid a laekage would generate, tolerable by the environment. This is the concept of the Maximum Allowable Amount of Leakage (MAAL). If one ask it to the environmental authorities, maybe the answer will be zero. Considering however, that every operating company should have a specialized team, for assessing the damage to the environment, caused by oil spills, the company, should be able to establish a MAAL which the damages can be faced, within reasonable cost and contingency efforts. This is the most subjective task of this matter. In a very informal way, even the environmental authorities can contribute to a reasonable MAAL, by taking data from other leakages. If the TAL were lower than MAAL, using a CVB, it means that you can use a CVB (and avoid a complex system), otherwise, you will have to search a better product, which would be a RTTM. The entire procedure is shown by Figure 1.

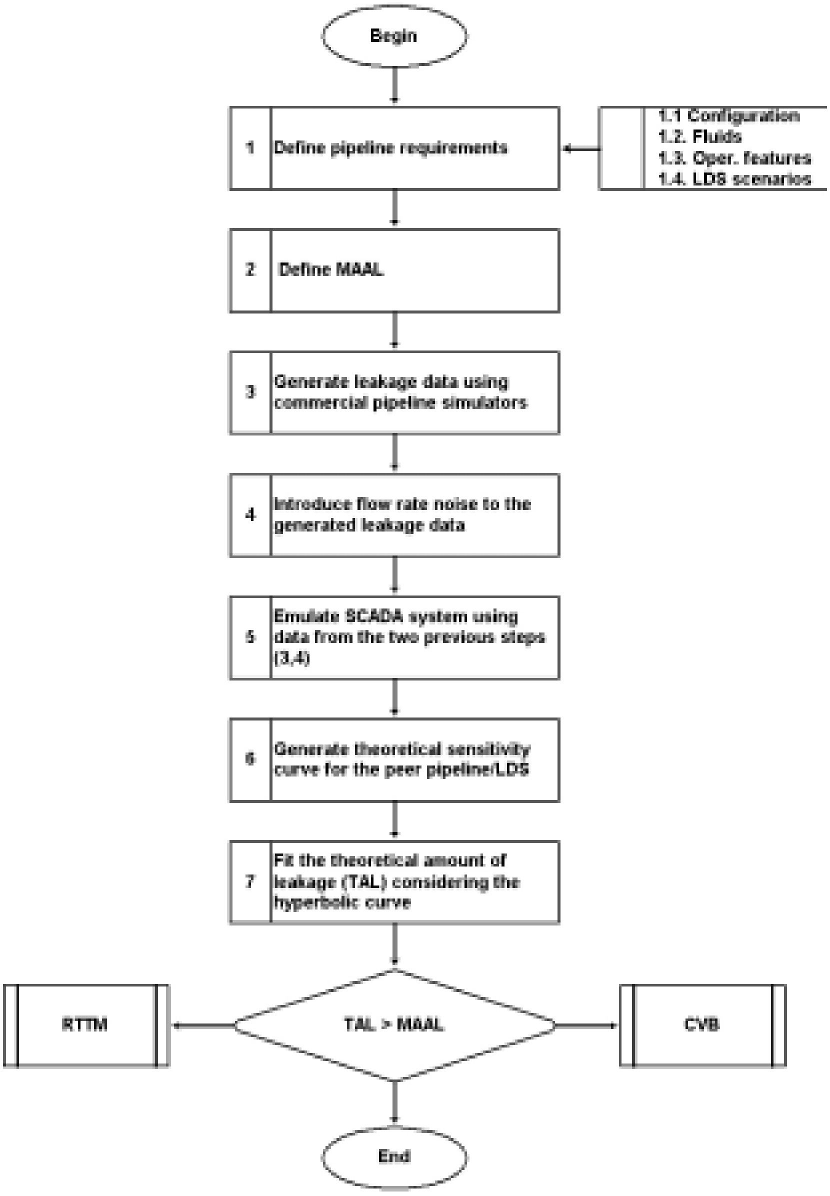

Figure 1 – The Evaluation Procedure

4 DISCUSSIONS

The best way to select LDS software is to test it on the pipeline in which it will be installed. This would allow us to know performance before buying. However, this is not practical, so the most cost-effective procedure is that shown in Fig. 1, which is called by the service companies as a “Theoretical Sensitivity Analysis”. There are some selection constraints as follows.

4.1 Suitability

Not every pipeline is suitable for a LDS. For example, there are no LDS approaches that can accommodate the piston alternate pumps used for high viscous fluids. The periodically varying flow rate doesn’t allow for a reasonable model. Also unsuitable are those lines that commonly operate at slack conditions. Other unsuitable situations include the following:

4.2 High Level Simulation Oversights

Simulations may overlook real-time operational problems. Variables like scan rate, for example, may be treated as constant. The simulated system also may not account for communication failure or instrument malfunctions. All the intermediate pieces of software, such as the driver that links the SCADA system information to the LDS, may be considered as having ideal behavior, with no time delay. Or, conversely, the LDS system that gathers information at the off-line simulation will also be treated as ideal.

4.3 Operational Fluctuations

Actual operations may show flow rate and pressure fluctuations that can´t be simulated easily. They are caused by aleatory effects, like pump malfunction, or valve aging. This may sometimes increase the overall uncertainties of the actual case, that won´t be fit the theoretical curve. Even the simulated aleatory flow rate uncertainty is not compensated for the effect on pressure and temperature. They are treated as three independent aleatory variables.

4.4 Real-time Tuning Omissions

For theoretical simulations, there are no tuning procedures. All variable changes are deterministic. It does not take into consideration, for example, the effects of an updated tuning procedure. This omission would degrade the real operation.

4.5 Simulator discretization approaches

The approach used by simulators to define their discretization, may not be the same used by the LDS. However, this will mostly affect a RTTM. The CVB is less affected, as it uses a ordinary linear approach. This problem can be minimized by using more than one simulator. Or, if available, by trying to get from both manufacturers (Simulator and LDS), the way they discretize their product.

4.6 Batches

All LDS´s and simulators treat batches as if they had a vertical profile with respect to the batch boundary. In real cases, there are boundary uncertainties that are not being accounted for. An example is the "S" profile of the interface between batches. It´s length is usually negligible when compared with the monitored segment total length. But there are some cases, especially those with ascending slow flow, where it can make a difference.

4.7 Sensitivity Behavior

The hyperbolic behavior of a sensitivity curve is just the expected behavior, i. e., sometimes, a completely extrange sensitivity curve takes place. Specially for LDS based in other technologies different from diferrential or material balances (the statistical packages). However, most of the CVB´s have the hyperbolic behavior, or a hyperbole can be fitted with acceptable errors.

4.8 Real Data

By the time this paper was written, PETROBRAS were conducting field tests in pipelines at Rio and São Paulo, using a comercial CVB product as a LDS, and two other comercial products as a pipeline simulator.

5 CONCLUSIONS

5.1 Cost considerations

The approach outlined here is less expensive than real operational tests. It does have a cost, but it hopefully is considerably lower than the cost of an inappropriate choice of a LDS. Sensitivity study costs are a function of pipeline complexity. They are frequently based on staff costs plus the cost of the computational resources. In this case, the computational resources are a substantial portion of the total cost. Assessments that require more than one simulator can be significantly more expensive.

5.2 Selection Roles

Selection has to be done internally by the operating company. An independent, third party company may be consulted to assess the vendor options. However, the final decision responsibility rests with the operating company. After selecting a given product, the operating company may decide to contract the simulation of the sensitivity curve to the vendor, which sometimes may be cost-effective.

5.3 Reliability

Theoretical sensitivity curves are, as the name indicates, theoretical. They may differ substantially from the actual sensitivity curve obtained from field test data. The curves are a good estimator of software behavior, for a given pipeline and product combination. However, successful application requires real world confirmation.

5.4 Difficulties for estimate MAAL

The Maximum Allowable Amount of Leakage is a non-technical decision, but it may be supported by technical estimates. It will vary from company to company, as well as from pipeline to pipeline. Estimations of MAAL are a team effort, requiring contributions many different divisions of the operating company. Acceptable corporate values can be determined by using the cooperative expertise from all relevant corporate areas.

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