LEAK DETECTION IN SIMPLE PIPELINES VIA COMPENSATED VOLUME BALANCE WITH LINEFILL CORRECTION

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Abstract. *This work presents leak detection and localization algorithms for pipelines based on integrated mass balance and head loss equations. The uncertainties in the mass balance equation terms give rise to a leak detection criterion whose algorithm accounts for packing and unpacking along the line enabling its operation at unsteady regimes. Based on flowrate and pressure data measured by SCADA system at the pipeline ends, the pressure is continuously evaluated through the solution of mass and momentum conservation equations. Representative results, obtained by a numerical approximation employing the method of characteristics with initial data originating from SCADA, indicate the efficiency of the leak detection and localization algorithms, especially for pipelines without batches and operating at steady and moderate transient regimes, respectively.*

Keywords*. Leak detection, leak localization, compensated volume balance with linefill computation, method of characteristics.*

1. Introduction

This work presents the development of leak detection and localization algorithms for pipelines carrying liquids (Luopa, 1992; Mears, 1992; Thompson and Skogman, 1984; Zhang, 1993). The first algorithm is based on the integrated balance of mass inside the line whereas the second one stems on the head loss equation for fully developed flows. Isothermal fluid flow is considered as a basic assumption. The leak detection criterion is established by determining appropriately the uncertainties of all the terms in the balance equation of mass. The leak detection algorithm takes into account the packing/unpacking phenomenon, which takes place in the line as a result of typical operational procedures, such as pump start-up and pump shutdown and valve operations. Such a feature enables its operation in not only steady but also unsteady regimes. The spatial pressure field is continuously evaluated by solving simultaneously the differential equations of conservation of mass and momentum. This task is performed by using the flowrate and pressure data, which is made available at the pipeline ends by the Supervisory Control and Data Acquisition (SCADA) system. The numerical solution of the differential equations is conducted with the aid of the method of characteristics by employing the data of the SCADA as initial values. The algorithm performance is evaluated by using a database of leaks, constructed within this work through numerical simulations. The system analyzed comprises a pipeline 50 km long, having a *scan rate* of 15 seconds, with leaks at two distinct sites along the line and leak flowrates ranging from 1.5% to 13% of the nominal flowrate under steady state and moderate and severe transient regimes. The obtained results indicate that the leak detection algorithm is a promising tool, especially for simple pipelines without batches. On the other hand, it is also shown that the localization algorithm is efficient as long as the line operates in steady and moderate transient regimes.

2. Leak detection via compensated volume balance methodology

The compensated volume balance equation, expressing the mass conservation principle for an instrumented pipe segment, written in terms of a standard volume for any time instant $t(-\infty,+\infty)$ may be expressed as:

$$\frac{d}{dt}\hat{V}(t)+\hat{Q}_o(t)-\hat{Q}_i(t)=-\hat{Q}_l(t) \tag{1}$$

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in which $\hat{Q}_o(t)$ and $\hat{Q}_i(t)$ represent the actual standard volumetric flowrate at the outlet and inlet of the pipeline segment, while $\hat{V}(t)$ denotes the standard volume quantity inside the pipeline; from now on denoted as linefill. The always nonnegative term $\hat{Q}_l(t)$ characterizes the actual instantaneous flowrate, being zero only in the absence of leak in the segment.

Denoting by $V(t)$, $Q_o(t)$ and $Q_i(t)$ the measured or estimated values of the actual quantities $\hat{V}(t)$, $\hat{Q}_o(t)$ and $\hat{Q}_i(t)$, which are available at any time instant (actually at discrete successive time instants characterized by a delay of one data acquisition interval – denoted as scan rate) and integrating Eq. (1) between $t-t$ and t (the current time instant) with $t > 0$, it comes that

$$F(t,t) = \left| V(t) - V(t-t) + \int_{t-t}^{t} \left[Q_0(x) - Q_i(x) \right] dx \right| \tag{2}$$

in which $V(t) - V(t-t)$ denotes the linefill variation and $\int_{t-t}^{t} \left[Q_0(x) - Q_i(x) \right] dx$ the integrated compensated volume difference. The summation of these two terms is denoted as integrated mass balance.

Since $V(t)$, $Q_o(t)$ and $Q_i(t)$ may present errors, the function $F(t,t)$ is not expected to be identically zero, even in the absence of leakage. $Q_o(t)$ and $Q_i(t)$, the outlet and inlet flowrates expressed in terms of standard volume, may be either directly measured or evaluated by measuring reference density, pressure, temperature and actual volumetric flowrate. On the other hand $V(t)$ is obtained solely from the following expression (Liou, 1993):

$$V(t) = \frac{1}{r_0} \int_0^{L(t)} r(x,t) A(x,t) dx \tag{3}$$

in which $L(t)$ and $A(x,t)$ denote the pipeline segment length and cross sectional area and $r(x,t)$ represents the mass density of the fluid(s) inside the pipe with r_0 being their reference value. Since $A(x,t)$, $r(x,t)$ and $L(t)$ depend on both temperature and pressure, accurate values for $V(t)$ require the previous knowledge of pressure and temperature fields along the line segment at any time instant as well as the products reference mass density. As a consequence, the position of existing interface batches along the line and appropriate equations of state must also be known.

A compensated volume balance leak detection criterion is automatically obtained whenever the uncertainty $dF(t,t)$ – associated with the computation of Eq. (2) – is known. If, for any $t > 0$ (in practice $t \geq \Delta t$ with Δt representing the used scan rate) and any time instant $t \in (-\infty, +\infty)$ the following inequality holds,

$$F(t,t) < dF(t,t) \tag{4}$$

then it may be concluded, with the same confidence level used to obtain $F(t,t)$, that there is no leak in the instrumented pipeline segment. The term $dF(t,t)$ represents the total uncertainty – arising from inlet and outlet flowrate measurements and from the linefill evaluation at $t-t$ and t.

Assuming F as function of the independent quantities $V(t-t)$, $V(t)$, $Q_o(t)$ and $Q_i(t)$ for all $t \in (-\infty, +\infty)$, the root-sum-square process (Moffat, 1988) may be used, leading to (Freitas Rachid et al, 2002)

$$dF(t,t) = \sqrt{\left[dV(t) \right]^2 + \left[dV(t-t) \right]^2 + \left[t dQ_o(x) \right]^2 + \left[t dQ_i(x) \right]^2} \tag{5}$$

with $dV(t)$ and $dV(t-t)$ representing the linefill uncertainties at time instants t and $t-t$ and the last two terms denoting the uncertainties associated with the outlet and inlet mass quantities at the time interval t, respectively.

The criterion stated in Eq. (4) states that an existing leak is reliably detected when the inequality (4) is no longer satisfied for any time instant $t \geq T$ and for a particular value of t – this latter parameter being usually referred to as time window.

It is remarkable that, in general, uncertainties associated with flow measurements (as well as pressure and temperature) depend not only on the quality of the instrumentation at the pipeline segment but also on the time instant, since the instrumentation behavior changes due to its usage and to the fluid present in the pipeline. In the present work the time dependence of $dF(t,t)$ has been assumed as due to the uncertainty associated with changes in the linefill only.

3. Basic equations for linefill computations

At this point some broadly used hypotheses (Wylie and Steeter, 1993) will be considered. First, a one-dimensional formulation adequately describes the fluid flow, since the pipeline diameters are significantly smaller than the instrumented segment length. Also a thin-walled pipe under small deformation is assumed, its material being isotropic, thermally sensitive with a linear elastic behavior and negligible radial and axial inertial effects. A Newtonian behavior is assumed for the fluid, flowing isothermally under low Mach numbers and the expression for steady-state viscous friction is supposed to be valid for transient regimes also. Besides, the wave propagation speed and the friction factor are assumed constant. Under the above mentioned hypotheses, the mass and linear momentum conservation for a compressible fluid flowing inside a pipe, after a convenient change in variables, may be stated as

$$\begin{aligned} &\frac{\partial H}{\partial t}+\frac{a^2}{Ag}\frac{\partial q}{\partial x}=0 \\ &\frac{\partial q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{f}{2DA}q|q|=0 \end{aligned} \qquad \text{for} \quad (x,t)\in(0,L)\times(-\infty,+\infty) \tag{6}$$

where *H* represents the head, *q* the volumetric flowrate, *A* the pipeline internal cross sectional area, *D* the pipe inner diameter, *L* its length, *g* the gravitational acceleration, *f* the Darcy-Weisbach friction factor and *a* the sonic velocity in the fluid within the compliant pipeline (Wylie and Steeter, 1993).

Based on volumetric flowrate, pressure and temperature data provided by SCADA system at the inlet $\{q_i(t), p_i(t), T_i(t)\}$ and the outlet $\{q_o(t), p_o(t), T_o(t)\}$ of the instrumented pipeline segment at successive time instants $t=...,t_{j-2},t_{j-1},t_j,t_{j+1},t_{j+2},...$ with scan rate $\Delta t = t_{j+1}-t_j = t_j - t_{j-1}$, an approximation for pressure field at these time instants may be obtained, allowing evaluating the linefill according to Eq, (3).

An average value for the sonic velocity, obtained from steady-state values for inlet and outlet temperature and pressure is assumed. The friction factor is also computed based on steady-state values for inlet and outlet head and volumetric flowrate, being updated with the help of the tuning process.

Since no exact solution for Eq. (6) is known, its numerical approximation is used to compute discrete values for the pressure (obtained from the head) within the pipeline segment at successive time instants, differing by a scan rate. Considering a constant sonic velocity, Eq. (6) is a quasi-linear hyperbolic system to be numerically approximated by employing the method of characteristics, whose implementation requires initial data. The method of characteristics allows transforming the partial differential equations (6) into a set of ordinary differential equations

$$\frac{dH^*}{dt}\pm\frac{dq^*}{dt}\pm\frac{aR}{L}q^*|q^*|=0 \quad \text{along} \quad \frac{dx}{dt}=\pm a \quad \text{with} \quad R:=\frac{fLq_r}{2aDA} \tag{7}$$

which should be approximately integrated along the characteristic curves. Since the sonic velocity is assumed constant, these curves are straight lines in the *x-t* plane with slopes $\pm a$.

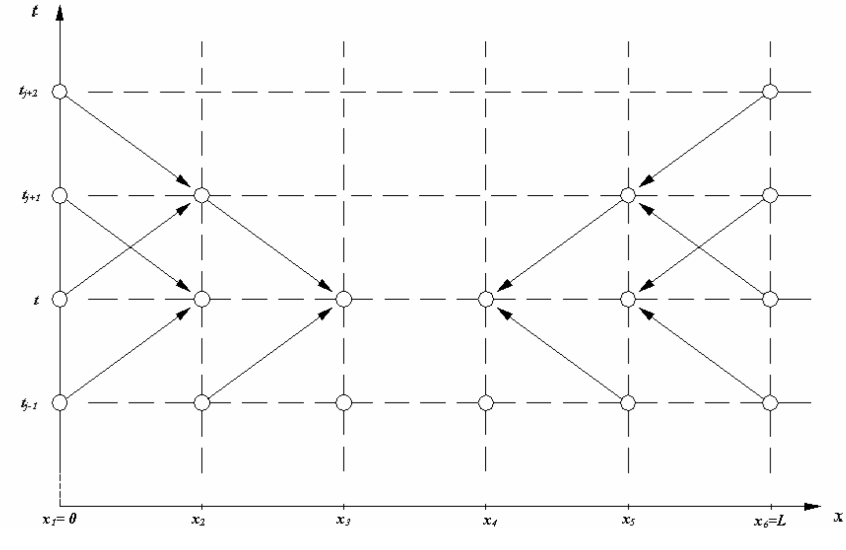

Figure 1. Grid of characteristics on a *x-t* plane for determination of the pressure field at a given time instant t_j

In the particular problem addressed in this work the information is available solely at the inlet and outlet of the instrumented pipeline segment – given, respectively, by $\{q_i(t), p_i(t)\}$ and $\{q_o(t), p_o(t)\}$. A specific procedure is required to determine this information in the domain interior is shown in Fig. 1, which depicts the grid of characteristics enabling to determine the pressure field at a given time instant t_j employing data at distinct time instants at $x = 0$ and $x = L$. The data previously known on the boundaries – specifically pressure and flowrate – is used to compute, via Eq. (7), the head within the domain, which, in turn, is used to calculate the pressure. The pressure field at each time instant will be later used to perform the linefill calculation.

Based on the fluid temperature $\overline{T}$ and on the pressure values at $0 = x_1, ..., x_{n+1} = L$ whose computation has been previously described, the linefill, defined in Eq. (3), at a time instant $t_{j,}$, is given by

$$V(t_j) = \frac{1}{r_0} \sum_{k=1}^{n} \int_{x_K}^{x_{K+1}} r(\overline{T}, p(x,t_j), r_0) A(\overline{T}, p(x,t_j)) dx \tag{8}$$

in which $r(\overline{T}, p(x,t_j), r_0)$ is obtained by means of the classical constitutive equation usually employed for slightly compressible fluids and $A(\overline{T}, p(x,t_j))$ is given by

$$A(\overline{T}, p(x,t_j)) = \frac{p D^2}{4}\left[1 + \frac{Dy}{Ee} p(x,t_j) + 2a(\overline{T} - 15)\right] \tag{9}$$

with E representing the pipe Young modulus, e its width and y defining how the pipeline is anchored and a is the linear thermal dilatation coefficient.

The leak detection algorithm requires the determination of the uncertainty associated with the linefill, which, for a generic time instant $t_{j,}$ is given by (Petherick and Pietsch, 1994)

$$dV(t_j) = \left\{ \left[\frac{\partial V}{\partial \overline{T}}(t_j) d\overline{T}\right]^2 + \sum_{i=1}^{n+1} \left[\frac{\partial V}{\partial p_{x_i}}(t_j) d p_{x_i}\right]^2 \right\}^{1/2} \tag{10}$$

in which $d\overline{T}$ is the uncertainty associated with the instrument for measuring the fluid temperature, p_{x_i} is the pressure at x_i and $d p_{x_i}$ its uncertainty at the time instant t_j.

4. Leak localization algorithm

Regardless the methodology used in the leak detection algorithm, most localization algorithms are based on the head loss equation obtained under the assumptions of steady-state developed flow, neglecting the localized head losses along the pipeline, the head variation at the inlet and outlet of the line, $\Delta\overline{H}$, and the fluid volumetric flowrate. Whenever there is a leak, the localization algorithm is operated, providing an estimate for its localization. The presence of a leak generates a variation on the head gradient at the spatial point where it takes place. Applying the head variation equation at both the left and right-hand sides of this point, the following equation estimates the leak localization x_L at the time instant t_j

$$x_L(t_j) = \frac{1}{q_i^2(t_j) - q_o^2(t_j)} \left(\frac{\Delta H(t_j)}{fL} - q_o^2(t_j) \right) \tag{11}$$

with ΔH representing difference in the head at both pipeline ends and q_i and q_o the inlet and outlet volumetric flowrates. Assuming no expressive variation between the values of f at both sides, its value obtained through the tuning process is employed. The uncertainty associated with the leak localization via Eq. (11) is given by:

$$d{x_L}^2(t_j) = \left[\frac{\partial x_L}{\partial H_i}(t_j) dH_i(t_j)\right]^2 + \left[\frac{\partial x_L}{\partial H_o}(t_j) dH_o(t_j)\right]^2 + \left[\frac{\partial x_L}{\partial q_i}(t_j) dq_i(t_j)\right]^2 + \left[\frac{\partial x_L}{\partial q_o}(t_j) dq_o(t_j)\right]^2 + \left[\frac{\partial x_L}{\partial f}(t_j) df\right]^2 \tag{12}$$

in which $\overline{H}_i$ and $\overline{H}_o$ stand for the head, $\overline{q}$ volumetric flowrate average, measured under steady-state flow assumption.

5. Numerical examples

In order to evaluate the performance of the leak detection system developed in this work – comprising leak detection and localization algorithms – experimental data is required. The absence of available experimental data in the literature, required the construction of a database – which has been developed employing the mechanical model used in the leak detection system elaboration. This model simulates the transient response of a simple hydraulic system – consisting of reservoirs and valves at both line ends, two data acquisition points (the distance between them being *L*, the pipeline segment length) and a leak, located at a previously known position L_v with controlled magnitude losses. Adequate change of the boundary conditions at the line ends leads – actually by means of the variation of height of both upstream and downstream reservoirs, combined with variation in the valves control – to the generation of transient regimes. The following relations have been used for head and flowrate in the present work

$$H_i = H_{0i}(1+A_i\sin(w_i t+f_i)\tilde{Z}_i)\ ,\ i\in\left(h_{in},h_{out}\right) \quad \text{and} \quad Q_i = K_i Z_i\sqrt{\Delta p}\ ,\ i\in\left(in,out\right) \tag{13}$$

in which H_{0i} is the reference head, A_i is the amplitude, w_i is the oscillatory frequency, f_i a difference in phase angle and $\tilde{Z}_i$ is a random oscillation parameter, whose purpose is to generate a noise, which is peculiar to this type of data. Also Q_i denotes inlet and outlet flowrate in the pipeline, K_i the head loss coefficient considering the valve 100% open, Z_i defines the valve opening percentage and Δp is the pressure difference upstream and downstream the valve. The leak at a given point of the pipeline is computed by

$$Q_v = K_v Z_v\sqrt{p_{inside}-p_{atm}} \tag{14}$$

with Q_v denoting the leakage at a given point within the pipeline, K_v the head loss coefficient, Z_v the percent of valve opening controlling the leak intensity and $p_{inside}-p_{atm}$ the pressure difference inside the pipeline at the leak position and the atmospheric outside pressure. The database is built in by combining Eqs. (7), (13) and (14).

Table 1. Performance of leak detection and localization algorithm for steady-state regime and time window $t = 100\Delta t$.

	Database					Leak Detection System					
No.	Leak Starting (min)	Leak Ending (min)	Leak Flowrate (Sm^3/h)	Leak Magn. (%)	Leak Position (km)	Leak Starting (min)	Leak Ending (min)	Leak Flowrate (Sm^3/h)	Leak Uncert. (Sm^3/h)	Leak Position (km)	Position Uncert. (km)
1	600.00	900.00	2.22	1.00	15.00	ND	ND	ND	ND	ND	ND
2	1200.00	1500.00	2.22	1.00	35.00	ND	ND	ND	ND	ND	ND
3	2393.00	2693.00	6.67	3.00	15.00	2407.25	2705.00	6.32	3.45	16.00	21.38
4	2993.00	3293.00	6.67	3.00	35.00	3008.75	3305.00	5.89	3.45	36.05	36.05
5	4186.00	4486.00	11.11	5.00	15.00	4194.50	4503.50	10.56	3.45	15.62	13.13
6	4786.00	5086.00	11.11	5.00	35.00	4795.50	5103.50	9.84	3.45	35.63	13.74
7	5979.00	6279.00	28.88	13.00	15.00	5982.75	6301.25	25.74	3.45	15.34	5.76
8	6579.00	6879.00	28.88	13.00	35.00	6582.75	6901.50	26.81	3.45	35.35	5.66
9	7772.00	8072.00	22.22	10.00	15.00	7776.75	8093.50	20.27	3.45	15.39	7.17
10	8372.00	8672.00	22.22	10.00	35.00	8377.00	8693.50	20.18	3.45	35.38	7.21

Table 2. Performance of leak detection and localization algorithm for transient regime with 50% severity and time window $t = 10\Delta t$.

	Database					Leak Detection System					
No.	Leak Starting (min)	Leak Ending (min)	Leak Flowrate (Sm^3/h)	Leak Magn. (%)	Leak Position (km)	Leak Starting (min)	Leak Ending (min)	Leak Flowrate (Sm^3/h)	Leak Uncert. (Sm^3/h)	Leak Position (km)	Position Uncert. (km)
1	600.00	900.00	2.22	1.00	15.00	ND	ND	ND	ND	ND	ND
2	1200.00	1500.00	2.22	1.00	35.00	ND	ND	ND	ND	ND	ND
3	2393.00	2693.00	6.67	3.00	15.00	2395.75	2693.75	6.72	3.45	19.53	19.73
4	2993.00	3293.00	6.67	3.00	35.00	2995.25	3294.75	6.46	3.46	40.21	20.58
5	4186.00	4486.00	11.11	5.00	15.00	4188.25	4487.50	11.19	3.45	16.92	12.26
6	4786.00	5086.00	11.11	5.00	35.00	4787.75	5088.25	10.57	3.46	39.66	12.85
7	5979.00	6279.00	28.88	13.00	15.00	5979.75	6280.75	28.09	3.46	15.70	4.59
8	6579.00	6879.00	28.88	13.00	35.00	6580.00	6881.75	29.81	3.46	37.31	5.31
9	7772.00	8072.00	22.22	10.00	15.00	7773.25	8073.75	21.98	3.45	16.07	6.20
10	8372.00	8672.00	22.22	10.00	35.00	8373.25	8674.75	22.22	3.46	36.36	6.24

Tables 1 and 2 present the performance of leak detection and localization algorithms for time window $t = 100\Delta t$ and steady-state regime and for time window $t = 10\Delta t$ and transient regime with 50% severity, respectively. The first column specifies the leak number and the five subsequent columns: the leak starting and ending, its flowrate magnitude (the ratio between the leak flowrate and the pipeline nominal flowrate) and, finally, the leak actual position related to the pipeline upstream end. Columns 7 to 12 show the leak detection system performance, indicating the identified leak beginning and ending time instants, the estimated leak flowrate, its uncertainty, the estimated leak position and its uncertainty, respectively. The label ND refers to a non-detected leakage.

Figure 2 depicts the time variation of the integrated mass balance, the linefill variation and the integrated mass difference. The linefill time variation illustrated in Fig. 2 – obtained by analyzing leak number 4 (the smallest detected leak presented in Table 1), depicts leaks under steady-state regime, since a continuous oscillation around zero is detected in the linefill variation. In other words, it shows a leak which is not taking place either in packing or unpacking periods. Table 1 allows concluding that the leak detection algorithm has been very accurate, with uncertainty around 3.45 Sm^3/h, regardless the leak magnitude considered.

In order to characterize the exact time instant in which the leak detection system identifies the smallest simulated leak, Fig. 3 presents a detail of Fig. 2, including the integrated mass balance uncertainty bars. Under steady-state operation, the leak detection exact time instant is characterized as the first time instant the upper limit integrated mass balance uncertainty bar is placed below the abscissa axis. In the particular case illustrated in Fig. 2, this time instant takes place around 3008.75 min.

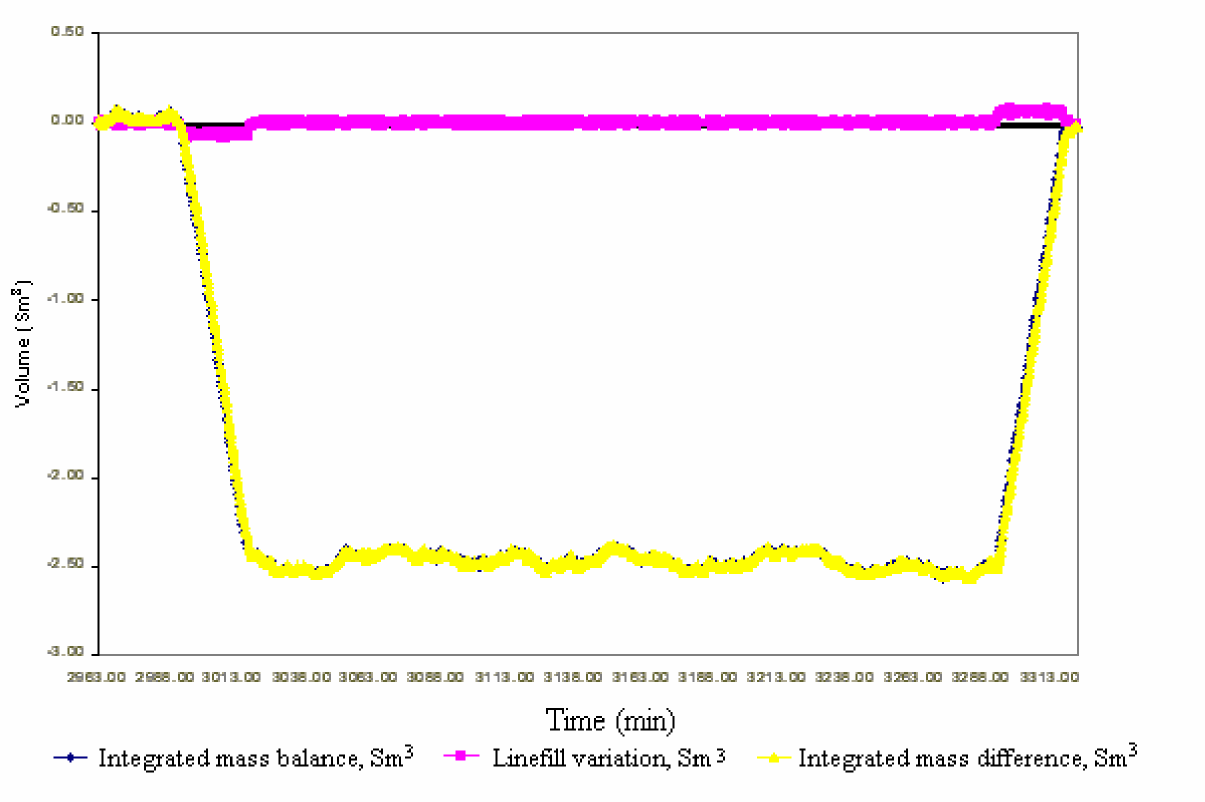

Figure 2. Integrated mass balance, linefill variation and integrated mass difference variation versus time. Leak No. 4, steady-state regime detected with time window $t = 100\Delta t$.

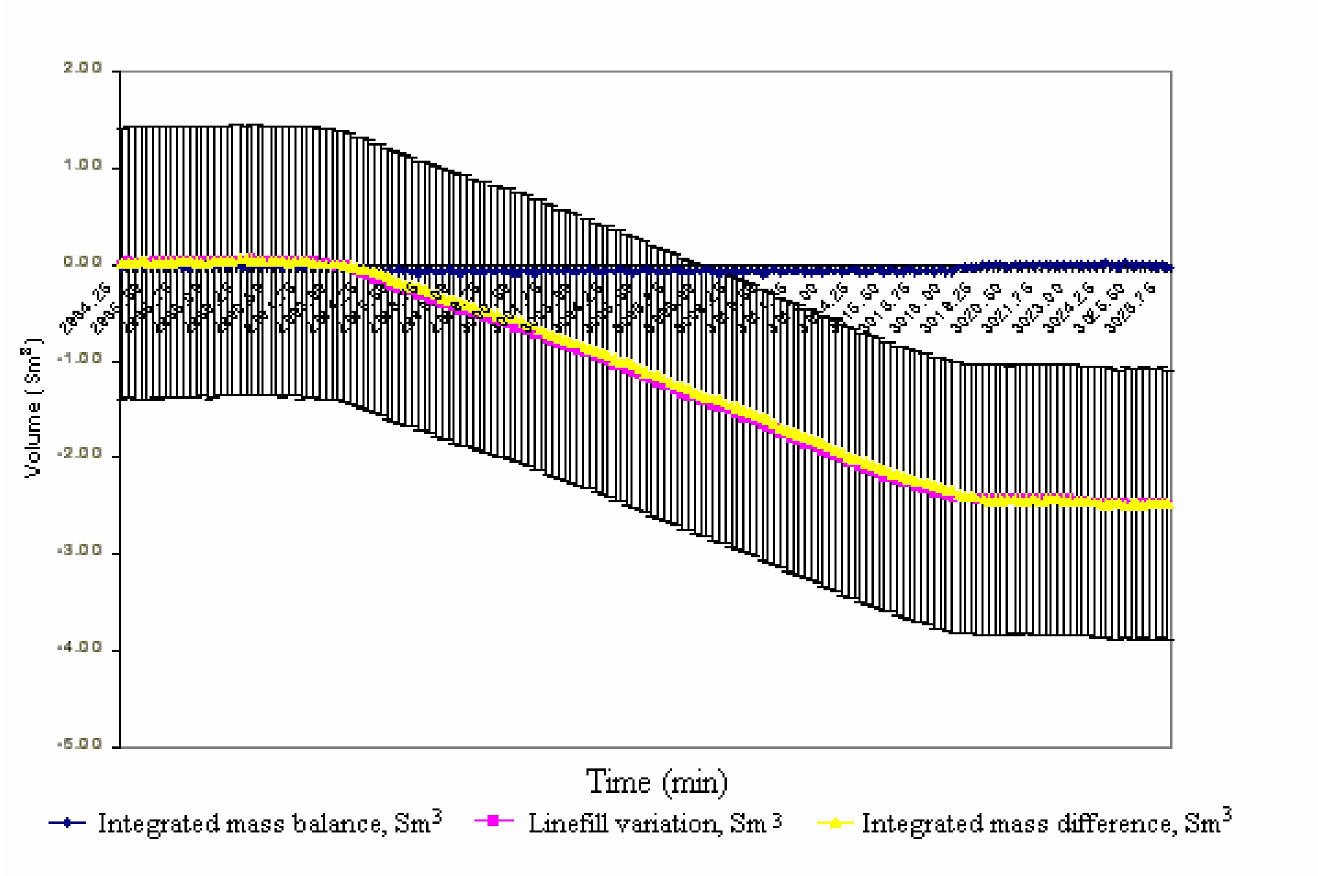

Figure 3. Detail of figure 2 at the leak beginning comprising the integrated mass balance uncertainty.

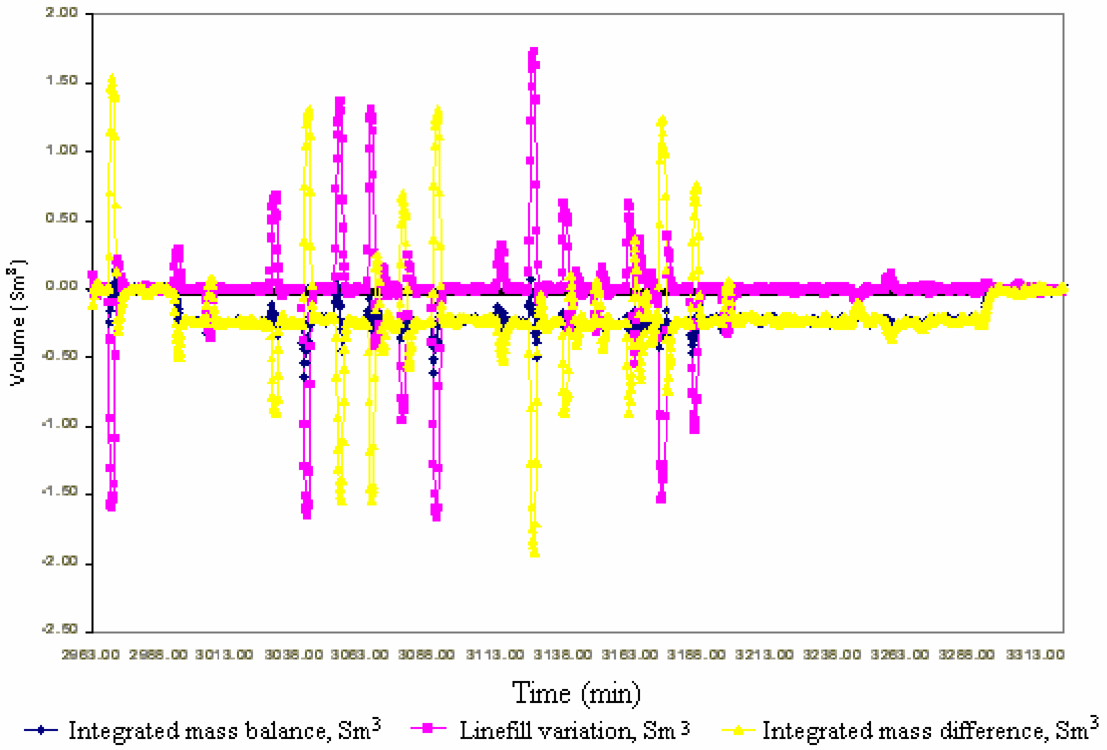

Figure 4. Integrated mass balance, linefill variation and integrated mass difference variation versus time. Leak No. 4, transient regime with 50% severity, detected with time window $t = 10\Delta t$.

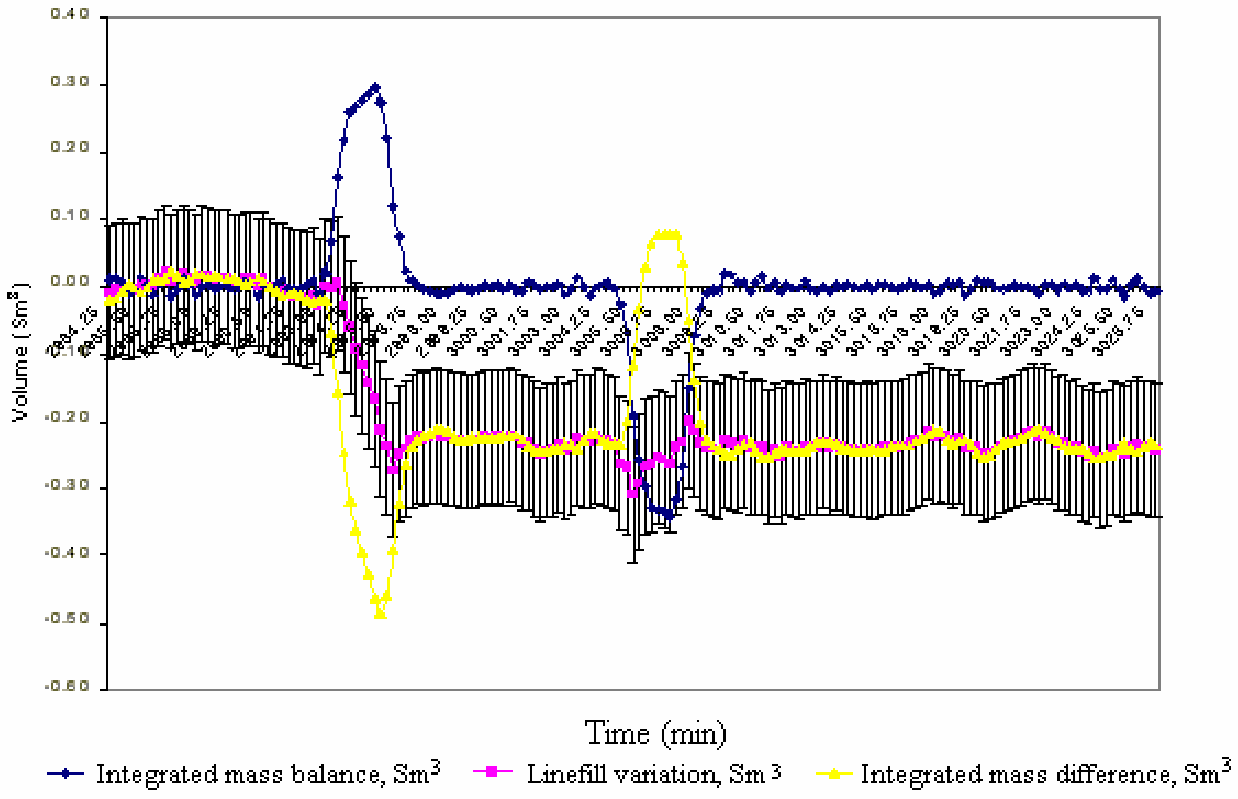

Figure 5. Detail of figure 4 at the leak beginning comprising the integrated mass balance uncertainty.

An example of transient regime with 50% severity and time window $t = 10\Delta t$ considered in Table 2 is depicted in Fig. 4. It analyzes leak number 4, the smallest detected leak presented in table 2, corresponding to 3.00% leak magnitude, detected after 2.25 minutes, being equivalent to 0.25 Sm^3 of leaked oil.

Figure 4 illustrates the time variation of the integrated mass balance, the linefill variation and the integrated mass difference. Unlike Fig. 2, obtained under steady-state regime, Fig. 4 depicts a significant time variation in the linefill.

The exact time instant in which the leak detection system identifies the smallest simulated leak is better characterized by observing Fig. 5, which presents a detail of Fig. 4, including the integrated mass balance uncertainty bars.

6. Concluding remarks

Leak detection and localization algorithms have been developed in this work as an integrating part of a leak detection system for pipelines carrying liquids. These algorithms have been achieved based on, respectively, compensated volume balance and head loss equations for developed flows applied to an instrumented pipeline segment. The leak detection criterion contemplates linefill variation, evaluated at every time instant considered in the data acquisition system. The pressure field is computed through the numerical solution of mass and linear momentum equations using as initial data pressure and flowrate fields measured by the SCADA system.

Results evaluation leads to some important conclusions. First the leak detection algorithm has shown a good performance for steady state and for both moderate and severe transient regimes. The smallest detectable leakage being a function of line instrumentation only. In fact, leak magnitude estimation is quite accurate, its uncertainty being almost independent from pipeline operation regime. Also, under a given operation regime, the smaller the leak magnitude, the greater the time interval required to detect it. Small time windows are able to detect very quickly large magnitude leaks, being, however, unable to detect small leakages. As a consequence, different time windows in the same leak detection system are a desirable feature, enabling quick leak detection.

Unlike the leak detection algorithm, the leak localization one has shown good performance for large and medium size leaks only. Also, the leak localization algorithm exhibits very high uncertainty for both moderate and severe transient operation regimes.

6. Acknowledgement

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