# SENSITIVITY CURVE OF VOLUME BALANCE LEAK DETECTION SYSTEMS FOR BATCHED PIPELINES

**Felipe Bastos de Freitas Rachid, rachid@vm.uff.br**
Laboratory of Liquid & Gas Transport - PGMEC/TEM - Department of Mechanical Engineering - Universidade Federal Fluminense

**José Henrique Carneiro de Araujo, jhca@ic.uff.br**
Laboratory of Liquid & Gas Transport - PGMEC/TCC - Department of Computer Science - Universidade Federal Fluminense

***Abstract.*** *Sensitivity curves of volume balance leak detection systems express the time required by the system to identify the presence of a leak of a certain magnitude, under several distinct scenarios. This curve may be assessed by means of theoretical analysis and is of great value when selecting a leak detection system for a particular pipeline. This work presents a simple theoretical development in which the sensitivity curve of compensated volume balance leak detection systems is derived for a pipeline carrying batches of products. The analysis carried out automatically provides the bounds with which the sensitivity curve is predicted, as a function of the system uncertainties. It is demonstrated that the performance of the leak detection systems degrades as the number of products in the line and the flow rate uncertainty increase.*

***Keywords:*** *sensitivity curve, volume balance leak detection, batched pipeline.*

## 1. INTRODUCTION

Compensated volume balance is a type of leak detection system currently employed in pipelines around the world. Such kind of methodology infers the existence of a leak based on the balance of mass inside the pipeline segment. It can operate during steady state as well as transient regimes and is usually referred to as volume balance systems with linefill correction [Petherick and Pietsch, 1994].

As a software-based leak detection system its performance is evaluated according to the four parameters [API 1155, 1995]: reliability, accuracy, robustness and sensitivity. Reliability is related to the probability of detecting a leak, given that a leak does in fact exist, and the probability of incorrectly declaring a leak, given that no leak has occurred. Accuracy is related to the precision with which the system estimates the leak parameters such as leak flow rate and leak location. Robustness is defined as a measure of the system to operate and provide useful information under degraded conditions. Finally, the sensitivity is a composite measure of the leak size that a system is capable of detecting and the time required for the system to detect it. The relation between leak size and response time is known as sensitivity curve and is dependent upon the nature of the leak detection system. Some types of leak detection systems have a peculiar sensitivity curve, such as the methods based on volume balance. On the other hand, other methodologies may even not possess a well-defined sensitivity curve such as those based on pattern recognition techniques [Liou and Tian, 1995].

The sensitivity curve of a leak detection system based on volume balance approach depends not only on the instrumentation installed on the line but also on the products being transported and on its operational regime. A rigorous theoretical derivation of the sensitivity curve has been presented in [Freitas Rachid et al., 2002] where permanent and transient scenarios were contemplated by assuming the existence of only one product inside the instrumented pipeline segment. However, oil pipelines usually transport sequentially more than one product (or grades of a same product) in a operation known as batch transfer.

The main objective of this paper is to derive a theoretical expression which aims to express the sensitivity curve of software-based compensated volume balance leak detection systems in batched pipelines. The analysis presented herein not only determines formally the expression of the sensitivity curve, for both permanent and transient regimes, but also gives the bounds with which this curve is identified as a function of the flow measurement and linefill uncertainties. As it will be shown, the presence of more than one product in the line alters the linefill uncertainty and so the sensitivity curve of the leak detection system. Depending on the accuracy of the flow rate meters installed at the inlet and at the outlet of the segmented line, the performance of the sensitivity curve can be severely degraded, as demonstrated in this paper by means of a simple numerical example.

## 2. VOLUME BALANCE EQUATION AND LEAK DETECTION CRITERION

To avoid misunderstanding, we have reserved, throughout this whole paper and unless stated contrary, the use of the parentheses to express functional dependence of a variable onto others. To begin with, let us consider the mass conservation principle for a instrumented pipeline segment written in terms of standard flow rate (i.e., the flow rate at a reference pressure and temperature $p_o$ and $T_o$) and for any time instant $t \in (-\infty, +\infty)$:

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

In the above equation, $\widehat{Q}_o(t)$ and $\widehat{Q}_i(t)$ stand for the actual standard volumetric flow rate at the outlet and at the inlet of the pipeline segment, whereas $\widehat{V}(t)$ represents the actual volumetric linefill. The term $\widehat{Q}_l(t)$, with $\widehat{Q}_l(t) > 0$, is the actual instantaneous standard volumetric leak rate. If $\widehat{Q}_l(t) = 0$, the segment line is in a non-leaking condition. Otherwise, the segment line is said to be leaking.

Let $V(t)$, $Q_o(t)$ and $Q_i(t)$ represent real-world measures and/or estimates of the actual values of $\widehat{V}(t)$, $\widehat{Q}_o(t)$ and $\widehat{Q}_i(t)$, respectively, which are made available at every time instant (in practice, at discrete and successive time instants which differ by a scan rate). So, integration of Eq. (1) between two time instants $t-\tau$ and $t$, with $\tau > 0$ and $t$ being the current time instant, yields the following function defined as:

$$F(t,\tau) := \left| V(t) - V(t-\tau) + \int_{t-\tau}^{t} [Q_o(\xi) - Q_i(\xi)]d\xi \right|. \tag{2}$$

Since $V(t)$, $Q_o(t)$ and $Q_i(t)$ are intrinsically not free of errors, the function $F(t,\tau)$ is not expected to be equal to zero in non leaking conditions. The volumetric flow rates $Q_o(t)$ and $Q_i(t)$ are measured at the outlet and at the inlet of the pipeline segment, whereas the volumetric linefill needs to be evaluated according to the following expression [API 1149, 1993] if there exists only one product in the line segment:

$$V(t) := \frac{1}{\varrho_o}\int_0^{L(t)} \varrho(x,t)A(x,t)dx. \tag{3}$$

In the above expression, $L(t)$ and $A(x,t)$ are, respectively, the length and the cross-sectional area of the pipeline segment, $\varrho(x,t)$ denotes the mass density of the fluid inside the line and $\varrho_o$ designates the mass density of the fluid at the standard conditions (i.e., at a reference pressure and temperature $p_o$ and $T_o$). The parameters $V(t)$, $Q_o(t)$, $Q_i(t)$, and $L(t)$ are functions of the time instant $t$, while $A(x,t)$ and $\varrho(x,t)$ have a functional dependence on both the time instant $t$ and the spatial position $x$ along the line segment. Since $\varrho(x,t)$, $A(x,t)$ and $L(t)$ are pressure and temperature dependent, accurate values of $V(t)$ are evaluated provided the pressure and temperature profiles along the pipeline segment are tracked in time.

The mass density of the fluid can be expressed in terms of its reference mass density $\varrho_o$ according to the API classification [API 1149, 1993];

$$\varrho(x,t) = \varrho_o C_p(T,p)C_T(T) \tag{4}$$

in which $C_p(T,p)$ and $C_T(T)$ stand for the volume correction factors for pressure and temperature, respectively. By denoting $\alpha$ the linear expansion coefficient of the pipe wall material, whose internal diameter is $D$ and thickness is $e$, the pipeline length and its cross-sectional area can be expressed in terms of its reference length $L_o$ and reference cross-sectional area $A_o$ as follows:

$$L(t) = L_o(1 + \alpha\Delta T) \tag{5}$$

$$A(x,t) = A_o(1 + \frac{Dp}{Ee} + 2\alpha\Delta T) \tag{6}$$

in which $\Delta T = T - T_o$ and $E$ represents the Young modulus of the pipe wall material.

Without loosing generality, if we admit that the reference line segment does not exceed 50 miles (about 80 km), then the following approximation of Eq.(3) can be employed [API 1149, 1993]:

$$V(t) = L_oA_oI(t) \quad \text{with} \quad I(t) = C_P(\bar{T},\bar{p})C_T(\bar{T})(1+\alpha\Delta\bar{T})(1 + \frac{Dp}{Ee} + 2\alpha\Delta\bar{T}) \tag{7}$$

in which $I(t)$ is the dimensionless linefill and $\bar{T} = \bar{T}(t)$, $\bar{p} = \bar{p}(t)$ and $\Delta\bar{T} = \bar{T} - T_o$.

When there exist batches of $n$ products in the pipeline, the linefill expression given by Eq. (3) must be rewritten in order to cope with the presence of different products. In this case, the reference mass density of the products must also be tracked in time since different products enter in the line. By disregarding the mixing phenomenon at the product's interface due to the dispersion of mass [Freitas Rachid et al., 2002], the linefill of a batched pipeline can be expressed as:

$$V(t) = \sum_{j=1}^{n} \frac{1}{\varrho_o^{(j)}} \int_{x_o^{(j-1)}}^{x^{(j)}} \varrho^{(j)}(x,t)A^{(j)}(x,t)dx \tag{8}$$

in which $x^{(j)}$ represents the actual spatial position of the interface between the $j$-th and the $j+1$-th products and is given by:

$$x^{(j)} = \left(x_o^{(j)} - x_o^{(j-1)}\right)\left(1 + \alpha\Delta\bar{T}^{(j)}\right) + x_o^{(j-1)} \tag{9}$$

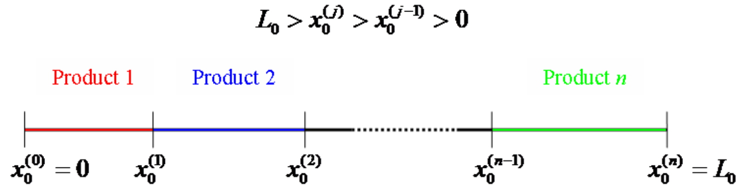


Figure 1. Pipeline reference configuration at a specific time instant with $n$ different products.

with $\Delta\bar{T}^{(j)} = \bar{T}^{(j)} - T_o$. In the above expression, $x_o^{(j)} = x_o^{(j)}(t)$, for $j = 1, \ldots, (n-1)$, represents the reference spatial position, at the current time instant $t$, of product's interface between the $j$-th and the $(j+1)$-th products, as depicted in Figure 1. As illustrated in Figure 1, it should be noticed that $x_o^{(0)} := 0$ and $x_o^{(n)} := L_o$.

Again, if we admit without loosing generality that the reference batch extension does not exceed 50 miles (about 80 km), then the following approximation of Eq.(8) can be adopted:

$$V(t) = \sum_{j=1}^{n} \left( x_o^{(j)}(t) - x_o^{(j-1)}(t) \right) A_o I^{(j)}(t) \tag{10}$$

$$I^{(j)}(t) = C_p^{(j)}(\bar{T}^{(j)}, \bar{p}^{(j)}) C_T(\bar{T}^{(j)})(1 + \alpha\Delta\bar{T}^{(j)}) \left( 1 + \frac{D\bar{p}^{(j)}}{Ee} + 2\alpha\Delta\bar{T}^{(j)} \right) \tag{11}$$

In the past expression, $x_o^{(j)}(t)$, for $j = 1, \ldots, (n-1)$, stands for the reference spatial position of the interfaces at the current time instant $t$ and can be expressed in terms of the instantaneous mean flow rate $\bar{Q}(t) := (Q_i(t) + Q_o(t))/2$ taking into account the flow rate measurements at the inlet and outlet of the line segment as:

$$x_o^{(j)}(t) = \frac{1}{A_o} \int_{t^{(j)}}^{t} \bar{Q}(\xi) d\xi \tag{12}$$

in which $t^{(j)}$ stands for the time instant the $j$-th product entered the pipeline.

Equations (10) and (12) clearly show that the linefill of a batched pipeline requires, besides the appropriate equations of state for the products, the knowledge of the batch interface positions, which in turn depends on the standard volumetric flow rate in the line.

Compensated volume balance leak detection systems make use of computational transient fluid flow models (based on the numerical solution of the continuity, momentum and energy equations along with suitable boundary conditions at he segment line) to estimate the linefill. Different models and algorithms have been proposed and analyzed in [API 1149, 1993] and [Thompson and Skogman, 1984].

If the uncertainty $\delta F(t, \tau)$, with which Eq. (2) is evaluated, is known, then a leak detection criterion of a software-based compensated volume balance leak detection system is readily available. If for any $\tau > 0$ (in practice, one should have $\tau \geq \Delta t$, with $\Delta t$ being the scan rate of the system) and any time instant $t \in (-\infty, +\infty)$ the following inequality holds,

$$F(t, \tau) < \delta F(t, \tau) \tag{13}$$

then it can be inferred that there is no leak in the line segment with a certain level of confidence. The term $\delta F(t, \tau)$ represents the total uncertainty, which is usually expressed with a certain confidence level, due to the overall measurement of the flow rate at the inlet and at the outlet and due to the evaluation of the linefill at the time instants $t - \tau$ and $t$.

For instance, if one assumes that $F$ is a function of the following independent quantities $V(t - \tau)$, $V(t)$, $Q_o(t)$ and $Q_i(t)$ for every $t \in (-\infty, +\infty)$; there is no mathematical errors associated with the evaluation of the integral in Eq. (2); there is no uncertainty associated with the time instants $t - \tau$ and $t$ and also the uncertainty associated with the flow measurements at the inlet and at the outlet are time independent, then we can use the root-sum-square process [Moffat, 1988] to write:

$$\delta F(t, \tau) = \sqrt{[\delta V(t)]^2 + [\delta V(t - \tau)]^2 + [\tau \delta Q_o]^2 + [\tau \delta Q_i]^2} \tag{14}$$

in which $\delta V(t)$ and $\delta V(t-\tau)$ stand for the linefill uncertainties, respectively, at the time instants $t$ and $t-\tau$, whereas $\delta Q_o$ and $\delta Q_i$ represent the uncertainty associated with the flow measurement equipments at the outlet and inlet, respectively.

The criterion (13) states that a leak, if it exists, will be detected reliably if it is no longer satisfied for a time instant $t \geq T$ and for a particular value of $\tau$. The parameter $\tau$ is customarily designated as time window. It should be remarked that, in general, the uncertainties associated with the flow measurements (and also pressure and temperature) depend not only on the quality of the equipment installed on the segment line but also on the time instant, as the instrumentation behavior changes due to its usage as well as due to the presence of different fluids in the line. Here, for the sake of simplicity, it has been assumed that the time dependence of $\delta F(t, \tau)$ in $t$ is solely due to the uncertainty associated with the change in the linefill.

## 3. SENSITIVITY CURVE

The connection between the actual standard volumetric balance of a leaking line - Eq. (1) with $\widehat{Q}_l(t) \neq 0$ - and the leak detection criterion of a typical compensated volume balance leak detection system, Eq. (13), is ultimately established when the time instant $t = T$ spent to the software to announce a leak is identified. So, let us suppose that a leak has occurred at $t = t^*$ and has been detected at $t = T$, with $T > t^*$. Thus, $\tau = T - t^*$ and the following relationship may be written from (13):

$$F(T, T - t^*) = \delta F(T, T - t^*). \tag{15}$$

On the other hand, integration of (1) between the time instants $t^*$ and $T$ gives:

$$\widehat{V}(T) - \widehat{V}(t^*) + \int_{t^*}^{T} [\widehat{Q}_o(\xi) - \widehat{Q}_i(\xi)]d\xi \quad = \quad -\int_{t^*}^{T} \widehat{Q}_l(\xi)d\xi = -\overline{\widehat{Q}}_l[T - t^*] \tag{16}$$

in which $\overline{\widehat{Q}}_l$ stands for the time average of the leak flow rate between the interval $[t^*, T]$. Since, within a certain confidence limit, we can assure that:

$$\widehat{V}(T) \in \mathcal{I}\Big(V(T); \delta V(T)\Big) \tag{17}$$

$$\widehat{V}(t^*) \in \mathcal{I}\Big(V(t^*); \delta V(t^*)\Big) \tag{18}$$

$$\int_{t^*}^{T} [\widehat{Q}_o(\xi) - \widehat{Q}_i(\xi)]d\xi \in \mathcal{I}\Big(\int_{t^*}^{T} [Q_o(\xi) - Q_i(\xi)]d\xi; [T - t^*]\delta Q_*\Big) \tag{19}$$

in which

$$\delta Q_* = \sqrt{[\delta Q_o]^2 + [\delta Q_i]^2} \tag{20}$$

stands for the total flow rate measurement uncertainty and $\mathcal{I}\big(y; z\big) := [y - z, y + z]$, the following bounds can be obtained for the actual amount of fluid leaked between $t^*$ and $T$ given by Eq. (16):

$$\overline{\widehat{Q}}_l[T - t^*] \in \mathcal{I}\Big(-[V(T) - V(t^*) + \int_{t^*}^{T} [Q_o(\xi) - Q_i(\xi)]d\xi]; [\delta V(T) + \delta V(t^*) + [T - t^*]\delta Q_*]\Big). \tag{21}$$

However, since by virtue of (Eq. 15)

$$V(T) - V(t^*) + \int_{t^*}^{T} [Q_o(\xi) - Q_i(\xi)]d\xi = -\delta F(T, T - t^*), \tag{22}$$

we can conclude that the time average leak rate - termed from now on as leak size for short - must be located within the bounds:

$$\overline{\widehat{Q}}_l \in \frac{1}{T - t^*}\mathcal{I}\Big(\delta F(T, T - t^*); [\delta V(T) + \delta V(t^*) + [T - t^*]\delta Q_*]\Big). \tag{23}$$

Since $\widehat{Q}_l(t)$ is not constant for $t \in [t^*, T]$, the term leak size actually represents a mean value of the leak flow rate form the time it has been initiated to the time it has been detected. Since the leak itself disturbs the flow regime in the line, the aforementioned concept of leak size is adequate when the line operates not only in transient but also in quasi steady state regimes. By taking the mean value of $\overline{\widehat{Q}}_l$ in Eq. (23) as being the most probable value of the leak size and by assuming for the sake of simplicity that $t^* = 0$, we finally arrive at the following relationship:

$$\overline{\widehat{Q}}_l = \frac{\delta F(T, T)}{T} = \sqrt{[\delta Q_*]^2 + \frac{[\delta V(T)]^2 + [\delta V(0)]^2}{T^2}}. \tag{24}$$

Equation (24) is the sensitivity curve of compensated volume balance leak detection systems. It defines the behavior of the leak size $\overline{\widehat{Q}}_l$ as a function of the elapsed time $T$ required by the software to detect it in both permanent and transient fluid flow regimes. It is worth noting that Eq. (24) is the same one presented by Liou (1993). However, in contrast to the approach presented here, steady state has be assumed as a basic assumption in [API 1149, 1993] work what restricts his analysis. Since $\delta V$ depends on the time instants $t = 0$ and $t = T$ in Eq. (24), it becomes clear that the performance of the leak detection system is directly affected by the operation of the pipeline at the time instant of the leak onset and at the time instant it was detected.

As it has been mentioned before, Eq. (24) describes the sensitivity curve whatsoever the fluid flow regime is and the number of products inside the pipeline segment. To better understand this feature, it first should be noticed that the linefill uncertainty $\delta V(t)$ depends on the way the linefill $V(t)$ is evaluated at the time instant $t$. Generally speaking, the linefill uncertainty depends on the accuracy of the methodology employed by the software to estimate it as well as on several features. Among them, we may cite pipeline instrumentation uncertainties, physical description of the pipeline (elevation profile, length, diameter, wall thickness) and fluid properties (reference mass density, viscosity, bulk modulus and thermal expansion coefficients) inaccuracies. Expressions for bounds on linefill uncertainty have been presented by [API 1149, 1993] and [Petherick and Pietsch, 1994] for steady state and transient conditions, to different volume balance approaches. The general relationship between the linefill uncertainty and the transient severity experimented by the segment line at the time instant $t$ has been explored in the paper [Freitas Rachid et al., 2002].

In this paper we will focus attention in the case the pipeline is transferring batches of different products. Although a batch transfer imposes an intrinsically unsteady-state regime in the pipeline, we admit, as a first approximation, that the fluid flow regime is permanent. In fact, if the transfer is carried out continuously (without stopping the pumping), then it can be shown that the fluid flow is almost in steady-state if the pump runs at constant angular speed. Before going a step further, its convenient to defined two important parameters of the sensitivity curves: the minimum response time and the minimum detectable leak.

Following the idea presented by Liou in [API 1149, 1993], the concept of minimum detectable leak arises when the limit of Eq. (24) is taken as the elapsed time approaches infinity, i. e. $T \to \infty$. In this case, the equality in (24) can be solved for $\overline{\widehat{Q}}_l$ in order to determine the size of the minimum detectable leak $[\overline{\widehat{Q}}_l]_{min}$;

$$[\overline{\widehat{Q}}_l]_{min} = \delta Q_* = \sqrt{[\delta Q_o]^2 + [\delta Q_i]^2} \tag{25}$$

which is essentially the overall uncertainty of the flow measurement in the line segment. The minimum detectable leak is independent of the fluid flow regime in the segment and also of the nature and the number of the products in line. Such a feature has already been noticed in other works, such as in [Petherick and Pietsch, 1994].

The concept of minimum response time arises when $\overline{\widehat{Q}}_l$ is equal to the reference volumetric flow rate in the segment line, i. e. $\overline{\widehat{Q}}_l = Q_r$. In such a case, the equality in (24) can be used to determine the minimum response time $T = T_m$. Since a leak of 100% of magnitude takes in general a short period of time to be detected, it is reasonable to assume that $\delta V(T_m) = \delta V(0) =$ and consequently,

$$T_m = \sqrt{\frac{2[\delta V(0)]^2}{[Q_r]^2 - [\delta Q_*]^2}}. \tag{26}$$

Equation (26) reveals that the minimum response time depends on the linefill uncertainty at the time instant the leak has begun ($t = 0$). Since, by hypothesis, the linefill uncertainty depends on the flow regime and the product in the line segment, then it becomes evident that minimum response time is affected by the presence of batches in the pipeline segment, as it will be seen later on this paper.

## 4. LINEFILL UNCERTAINTY OF SINGLE PRODUCT AND MULTIPRODUCT PIPELINES

Once the linefill expression has been derived for a single product as well as for multiple products inside the line segment, the linefill uncertainty can be computed provided some additional assumptions are taken into account. By assuming steady or quasi-steady-state regime and that the mean temperature $\bar{T}$ and the mean pressure $\bar{p}$ are independent variables, we can use the root-sum-square process [Moffat, 1988] in Eq. (7) to write:

$$\delta V(t) = \sqrt{(L_o A_o)^2 \left[ \left( \frac{\partial I}{\partial \bar{T}} \delta \bar{T} \right)^2 + \left( \frac{\partial I}{\partial \bar{p}} \delta \bar{p} \right)^2 \right]} \tag{27}$$

Analogously, if besides the aforementioned assumption we admit the batched pipeline operates with constant standard volumetric flow rate, then we can employ the root-sum-square process [Moffat, 1988] in Eq. (10) to express the linefill uncertainty of the batched line segment as:

$$\delta V(t) = \sqrt{\sum_{j=1}^{n} \left[ \left( x_o^{(j)} - x_o^{(j-1)} \right) A_o \right]^2 \left[ \left( \frac{\partial I^{(j)}}{\partial \bar{T}^{(j)}} \delta \bar{T}^{(j)} \right)^2 + \left( \frac{\partial I^{(j)}}{\partial \bar{p}^{(j)}} \delta \bar{p}^{(j)} \right)^2 + \left( I^{(j)}(t) \frac{\delta \bar{Q}}{\bar{Q}} \right)^2 \right]} \tag{28}$$

Expression Eq. (27) has been originally derived by Liou in [API 1149, 1993] and explored in many other works (see for example, [Petherick and Pietsch, 1994]) to theoretically evaluate the leak detection potential of pipelines carrying a single product under stabilized operational regimes. By comparing the Eq. (27) and Eq. (28) we can see that the linefill uncertainty in batched pipelines depends not only on the mean pressure and temperature uncertainties in each pipeline segment but also on the volumetric flow rate uncertainty, on the dimensionless linefill of each product and on the interfaces' position along the pipe on the reference configuration. Since the relative values assumed by these variables can vary significantly from case to case, a better picture about the influence of these parameters on the leak detection performance can only be evaluated by considering actual quantitative examples, as illustrated in the next section.

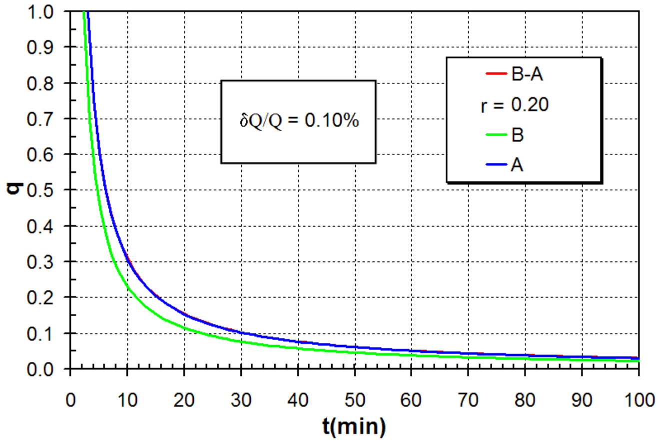


Figure 2. Sensitivity curves for a line with different products and with relative uncertainty of flow rate equal to 0.1%. The blue and green curves show the situation when products A (gasoline) and B (diesel) are alone in the line, respectively. The red curve is for a batched pipeline with products B and A, having the interface traveled 20% of the line extension.

## 5. NUMERICAL EXAMPLE

To quantify the influence of the presence of batches on the sensitivity curve of a volume balance leak detection system we appeal to a numerical example in which actual fluid properties and real world uncertainties are considered. For this purpose, consider a instrumented line segment which transports two products diesel (Product B, $j = 1$) and gasoline (Product A, $j = 2$), whose mass reference densities (at $p_o = 1$ atm and $T_o = 15.6$ °C) are $\varrho_o^{(1)} = 860$ kg/m$^3$ and $\varrho_o^{(2)} = 760$ kg/m$^3$. The line is isothermal being the temperature equal to $\bar{T} = \bar{T}^{(1)} = \bar{T}^{(2)} = 25.0$°C. The kinematic viscosities of the products at the this operational temperature are $\nu^{(1)} = 9.0$ cSt and $\nu^{(2)} = 0.8$ cSt. For the sake of simplicity, the pipeline profile is assumed to be flat. The pipeline properties are presented in Table 1.

Table 1. Pipeline properties of the example considered.

| Properties | |
|---|---|
| Length (km ) | $L_o = 80$ |
| Diameter (in) | $D = 12$ |
| Diameter-to-thickness ratio (dimensionless) | $D/e = 75$ |
| Young modulus of elasticity (GPa) | $E = 200$ |
| Linear thermal expansion coefficient (°C$^{-1}$) | $\alpha = 1.4\text{E}^{-5}$ |
| Relative roughness (dimensionless) | $\epsilon = 0.001$ |

The pipeline is assumed to operate with a constant standard volumetric flow rate of $\bar{Q} = Q = 245$ m$^3$/h all the time during the batch transfer. The mean pressure in each segment of the pipeline is taken as the arithmetic mean of the pressures at the beginning and at the end of this segment. The gauge pressure at the outlet is assumed to be constant and equal to 1 kgf/cm$^2$. The expressions of the API [API 1149, 1993] are used to compute the fluid coefficients $C_p(p,T)$ and $C_T(T)$ and its derivatives, according to the reference mass density of the products.

In what follows, we construct the sensitivity curves, $q := \overline{\overline{Q}}_l/\bar{Q}$ as a function of $T$, using Eqs. (24), along with (27) or (28) for three distinct situations: when only product A is in the line segment, when only product B is in the segment line and also when both products A and B are in the line segment by considering different relative positions of the interface in the line, $r := x_o^{(1)}/L_o$; $r = 0.2$, $r = 0.5$ and $r = 0.8$. To characterize the influence of the flow uncertainty on the sensitivity curve different values of the flow rate uncertainty $\delta Q_i = \delta Q_o = \delta Q$ are also considered: $\delta Q/Q = 0.1\%$ and $\delta Q/Q = 0.5\%$. In all of these cases we have admitted $\delta\bar{p} = 0.5$ kgf/cm$^2$ and $\delta\bar{T} = 1.0$ °C.

Figure 2 presents the sensitivity curve of the system when $\delta Q/Q = 0.1\%$ and the interface is positioned at $r = 0.2$. To better characterize the influence of the batch on the system performance, the sensitivity curves when products A and B are alone in the line segment are also shown in this figure. As expected, we can see that the sensitivity curve of the system depends on the product in the line, since different curves are obtained for the products A and B in Fig. 2. In particular, it can be seen in Fig. 2 that it takes less time to detect a leak of a same magnitude with product B in line than with product

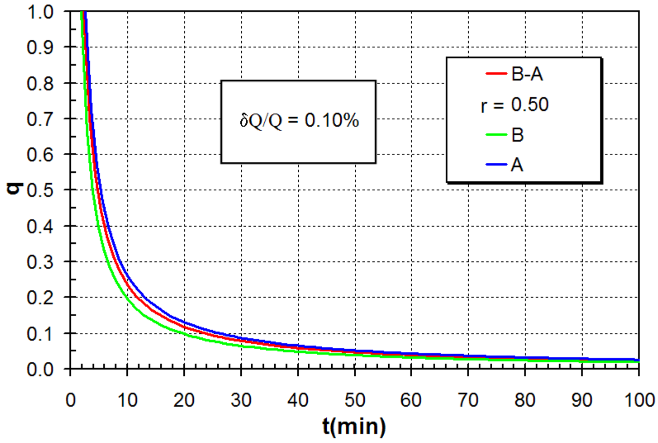


Figure 3. Sensitivity curves for a line with different products and with relative uncertainty of flow rate equal to 0.1%. The blue and green curves show the situation when products A (gasoline) and B (diesel) are alone in the line, respectively. The red curve is for a batched pipeline with products B and A, having the interface traveled 50% of the line extension.

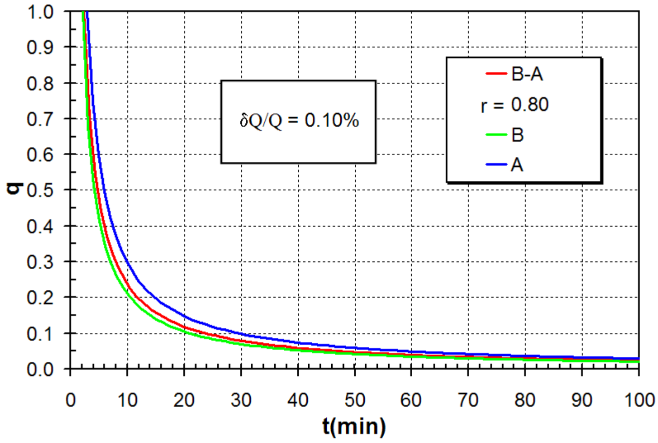


Figure 4. Sensitivity curves for a line with different products and with relative uncertainty of flow rate equal to 0.1%. The blue and green curves show the situation when products A (gasoline) and B (diesel) are alone in the line, respectively. The red curve is for a batched pipeline with products B and A, having the interface traveled 80% of the line extension.

A. A leak of 20% of magnitude is detected in 11 min when the line is filled with diesel (product B). However, it takes 15 min to detect this same leak when gasoline (product A) fills the entire line. In spite of this difference, the minimum detectable leak is the same 0.14% for the three cases: product A, product B or product A and B in the line. When there is a batch of products A and B in the line, with the interface at $r = 0.2$, the sensitivity curve coincides with the one for the case in which product A fills the whole line (see Fig. 2). Since in this batch product A occupies 80% of the line extension, we can infer that the additional term in the linefill uncertainty due to the volumetric flow rate (3rd term in the right-hand side of Eq.(28)) corresponds approximately up to 20% in the linefill of product A.

As the interface travels downstream the sensitivity curve of the batched pipeline tends to the one of product B, as it has been shown in Figs. 3 and 4 when the interface occupies the relative position in the segment line of $r = 0.5$ and $r = 0.8$, respectively. The minimum response time for the segment line is of 2.97 min and of 2.10 min when the line is filled with only product A (gasoline) and only product B (diesel), respectively. The minimum response time for the batched pipeline belongs to the interval (2.10;2.97) min and depends on the relative position of the interface on the line.

The behavior described in the past paragraphs is completely altered when the overall volumetric flow rate uncertainty increases to $\delta Q/Q = 0.5\%$. In this case the linefill uncertainty term associated to the flow rate uncertainty becomes preponderant with respect to the ones related to the pressure and temperature uncertainties. Figures 5, 6 and 7 illustrate the sensitivity curves for the batched pipeline when the interface is positioned at $r = 0.2$, $r = 0.5$ and $r = 0.8$, respectively. Contrary to what was observed in the past case in which $\delta Q/Q = 0.1\%$ (see Figs. 2, 3 and 4), the sensitivity curve of

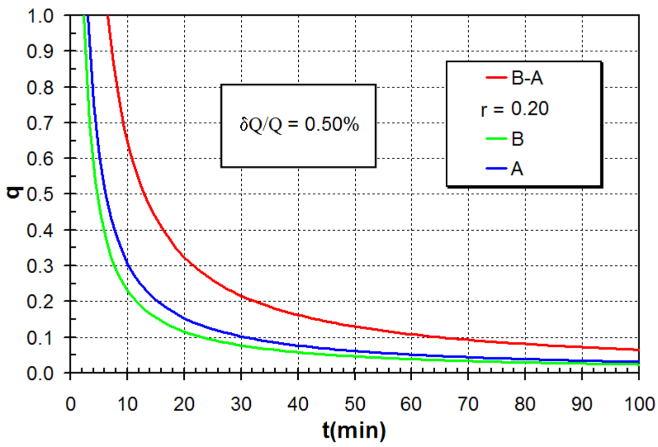


Figure 5. Sensitivity curves for a line with different products and with relative uncertainty of flow rate equal to 0.5%. The blue and green curves show the situation when products A (gasoline) and B (diesel) are alone in the line, respectively. The red curve is for a batched pipeline with products B and A, having the interface traveled 20% of the line extension.

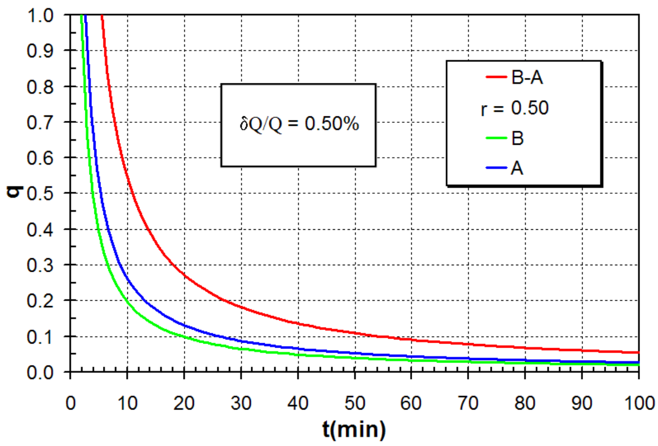


Figure 6. Sensitivity curves for a line with different products and with relative uncertainty of flow rate equal to 0.5%. The blue and green curves show the situation when products A (gasoline) and B (diesel) are alone in the line, respectively. The red curve is for a batched pipeline with products B and A, having the interface traveled 50% of the line extension.

the batched pipeline lays at the right of the curves for the products A and B, whatever the position of the interface in the line segment is, as it can be seen in Figs. 5, 6 and 7. It shows that the sensitivity curve of the system for batched pipeline is degraded. A leak of size 20%, which is detected in 11 min when the line is filled with diesel (product B) and in 15 min when gasoline (product A) fills the entire line, takes now in average 30 min to be detected. Although the minimum detectable leak remains the same, the minimum response time increases to 5.45 min, what demonstrates that flow rate uncertainty may be a critical parameter for volume balance leak detection systems in batched pipelines.

## 6. CONCLUDING REMARKS

It has been presented in this paper a theoretical development which allows the determination of the sensitivity curve of general compensated volume balance leak detection systems for multiproduct pipelines. Besides of its determination, the analysis gives the bounds of it as a function of the flow rate measurement and linefill uncertainties. The analysis demonstrates that the performance of a leak detection systems of this nature is directly affected by the operation of the pipeline at the time instant of the leak onset and at the time instant the leak is effectively detected. Moreover, depending on the instrumentation quality used for flow measurement, it is shown that the sensitivity curve of batched pipelines can be severely degraded. The greater the flow rate uncertainty is, the worse the sensitivity curve in batched pipelines becomes.

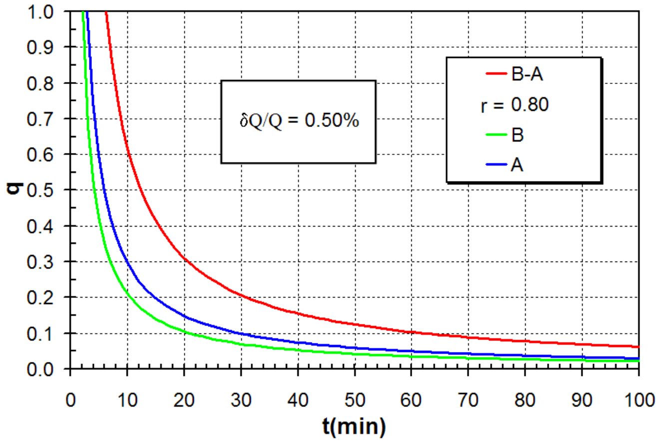


Figure 7. Sensitivity curves for a line with different products and with relative uncertainty of flow rate equal to 0.5%. The blue and green curves show the situation when products A (gasoline) and B (diesel) are alone in the line, respectively. The red curve is for a batched pipeline with products B and A, having the interface traveled 80% of the line extension.

## 7. ACKNOWLEDGMENTS

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## 9. RESPONSABILITY NOTICE

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