MIXING VOLUME DETERMINATION IN BATCH TRANSFERS THROUGH SONIC DETECTORS

Renan Martins Baptista - e-mail: renan@cenpes.petrobras.com.br
Exploitation Division
Research and Development Center
Petrobras - Petróleo Brasileiro S.A.
Cidade Universitária, Q.7 - Ilha do Fundão
Rio de Janeiro, RJ, 21949-900, Brazil
Felipe Bastos de Freitas Rachid *- e-mail: rachid@mec.uff.br
Department of Mechanical Engineering
Universidade Federal Fluminense
Niterói, RJ, 24210-240, Brazil
José Henrique Carneiro de Araujo - e-mail: jhca@dcc.ic.uff.br
Department of Computer Science
Universidade Federal Fluminense
Niterói, RJ, 24210-240, Brazil

Abstract. *It has been reported in this paper an experimental methodology to evaluate mixing volumes in batch transfers by means of sonic detectors. Mixing volumes have then been computed in a transfer of diesel/gasoline carried out through a pipeline operated by Petrobras for different interface points. It has been shown that an adequate choice of the interface points is crucial for keeping the mixing volume uncertainty within acceptable limits.*

Key-words: *Mixing volume, Batch transfer, Sonic detectors*

1. INTRODUCTION

The transfer of different products in a same pipeline is a common practice in the petroleum industry. Such a task may be carried out by using or not scrapers to separate the batches, according to the product features and pipeline characteristics. When scrapers are not employed, a mixture zone develops at the products' interface, which increases in length as it travels along the line until reach the receiving point. In these cases, the feasibility and economics of such operations depend upon both the extent of the mixing
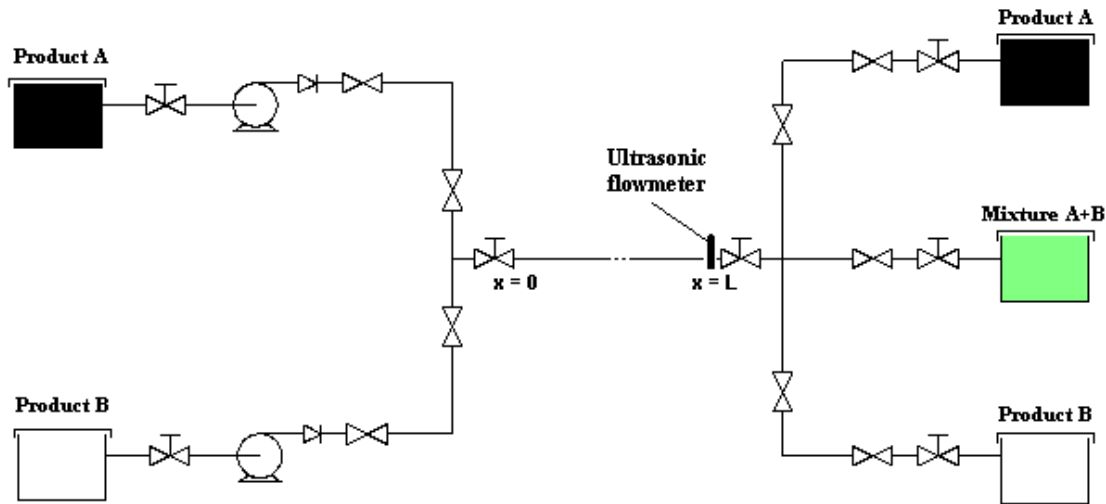
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*Corresponding author.

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Figure 1: Schematic representation of a batch transfer installation in a pipeline.

region and the capability to properly detect it. As a consequence, the minimization of the mixing zone without altering the products' specifications should always be pursued.

Among others, sonic and gravitometers interface detectors are currently used in batch detection. Sonic detectors identify the interface by monitoring sonic velocity changes in the fluid flow at the delivery point of the pipeline. Gravitometers do the same task by noticing changes in specific gravity. Since sonic detectors can discern interfaces between two petroleum products having the same density, it becomes quite attractive in pipelines that transport different grades of a same product and thus is preferred.

Once the interface sonic signature is recorded, it must be transformed into a concentration curve in real time so that the start and finishing of the mixture zone can be properly identified, through prior specification of the interface concentration points. Through suitable valve switching, the pipeline operator directs the contaminated mixing volume to separate temporary tanks for later reprocessing or reinjection at other transport operation. From the practical viewpoint, the mixing volume is one of the parameters used to appraise the efficiency of a batch transfer. It is customarily calculated and reported in the literature by employing interface points with admissible concentrations of 1%-99% (Austin and Palfrey, 1964; Hara et al., 1979; Botros, 1984).

This paper presents a simple methodology to compute mixing volumes through sonic signature registers. The great advantage of the proposed method is that it automatically gives the elements necessary to perform the mixing volume uncertainty analysis . Experimental tests were carried out in a pipeline (199,9 km long having 10" of diameter) conveying batches of gasoline/diesel. Sonic velocity and flow rate were measured using a clamp-on transit-time ultrasonic flow meter with an aquisition frequency of 0.2 Hz. As one of the contributions of this paper, it is shown that mixing volumes evaluated with interface points of 1%-99% will have extremely high uncertainties no matter how accurate the detector is.

2. EXPERIMENTAL SETUP AND INSTRUMENTATION

Before presenting the experimental methodology, it is convenient to describe how a batch transfer is conducted in practice and also to precisely define the mixing volume.
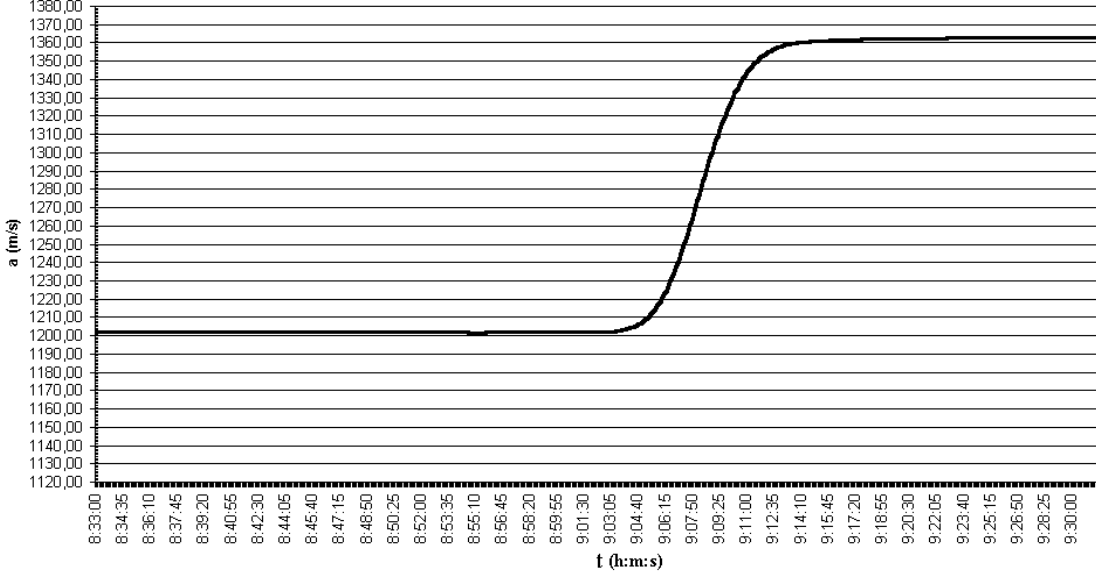
Figure 2: Sonic velocity as function of time at $x = 199.9 km$.

Consider the schematic pipeline installation shown in Fig 1 which is used to sequentially pump two distinct products designated as "A" and "B". The pipeline has a constant diameter d and a length L, which is measured from the junction of the pump discharge lines until the receiving point at the other pipeline end. By an appropriate valve switching, at time instant $t = 0$, the pumping of fluid "A" is interrupted and, at the same time, pumping of fluid "B" is started so that fluid "B" begins to push fluid "A" along the line. Let us designate by $C_i(x, t) \in [0, 1]$, with $i \in \{A, B\}$, the time-averaged mean concentration in volume of fluid i within the mixture at the cross-section of the pipeline as a function of the spatial position x along the pipe and the time t. Thus, the beginning of the sequential transfer can be described in terms of C_B by,

$$C_B(x = 0^-, t = 0) = 1 \text{ and } C_B(0^+ \leq x \leq L, t = 0) = 0 \tag{1}$$

or in terms of C_A by,

$$C_A(x = 0^-, t = 0) = 0 \text{ and } C_A(0^+ \leq x \leq L, t = 0) = 1 \tag{2}$$

since, for all (x, t), the following relationship must hold:

$$C_A + C_B = 1. \tag{3}$$

During the passage of products through the pipeline a mixing zone is formed at the boundary of the two adjacent products. Such a zone of contaminated material increases in length as it travels along the line and can be characterized by the interval $[x_f, x_i] \subset [0, L]$, with $x_f = x_f(t)$ and $x_i = x_i(t)$, such that $1 = C_B(x = x_f, t) > C_B(x, t) > C_B(x = x_i, t) = 0$ or $0 = C_A(x = x_f, t) < C_A(x, t) < C_A(x = x_f, t) = 1$, for $x \in (x_f, x_i)$. When the beginning of the mixing zone reaches the pipeline end, that is $x_i(t) = L$, the flow is directed toward the mixture tank. Finally, when the end of the mixture zone reaches the position $x_f(t) = L$, the fluid flow is conducted to the tank containing product "B". In practice, small degrees of contamination are allowed to take place at the beginning and at the end of the mixing zone, which are expressed in terms of the

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maximum admissible concentration C_{BA} and C_{AB}, respectively. Once these values (which are not necessarily equal) have been chosen in such a way that the products technical specifications are not altered, the contaminated volume, which should be stored in the tank for later reprocessing, is defined as:

$$V_c = \int_{t_{BA}}^{t_{AB}} Q(t) \, dt \qquad (4)$$

in which $Q(t)$ denotes the volumetric flow rate at the receiving point (that is, the position $x = L$), t_{BA} is the time instant associated to the arrival of the beginning of the contaminated interface with concentration C_{BA} at $x = L$ and t_{AB} is the time instant associated to the arrival of the end of the contaminated interface with concentration C_{AB} at $x = L$. In other words, t_{BA} and t_{AB} are such that $C_B(x = L, t = t_{BA}) = C_{BA}$ and $C_A(x = L, t = t_{AB}) = C_{AB}$, respectively.

The passage of the mixing zone at $x = L$ was detected by continuous monitoring the sonic velocity and the flow rate at this point. To do so, it was used a clamp-on transit time ultrasonic flowmeter with constant aquisition frequency of $0.2Hz$ (Couto, 1998), as shown in Fig 1.

The experimental data of sonic velocity $a(t_j)$ and flow rate $Q(t_j)$ at $x = L$ during the passage of the batch were recorded in a data file for $j = 1, \cdots, N$; being N the total number of registers. Since the data aquisition was done with constant frequency $\Delta t = t_{j+1} - t_j = 5s = constant$.

To better characterize the notation used herein, consider the following time instants $t_o < t_{BA} < t_{AB} < t_l$ of the database time chronology

$$t_1, \, \ldots, \, t_r, \, \ldots, \, t_o, \, \ldots, \, t_{p-1}, \, t_p, \, t_{p+1}, \, \ldots, \, t_{k-1}, \, t_k, \, t_{k+1}, \, \ldots, \, t_l, \ldots, \, t_s, \, \ldots, t_N,$$

in which t_o stands for the last time instant before the passage of the mixture zone (that is, for $t \leq t_o$ it is registered in the database the presence of fluid "A" with 100% purity) and t_l the first time instant after the passage of the mixture zone (that is, for $t \geq t_l$ it is registered in the database the presence of fluid "B" with 100% purity).

As experimental setup it was used a pipeline, 10" of diameter and $199.9km$ long, operated by Petrobras, with a topographical level difference between $x = 0$ and $x = L$ of $-895m$. The fluids transported were gasoline and diesel, being the gasoline the leading fluid ($\gamma_A = 734kgf/m^3$, $\nu_A = 0.9cSt$) and the diesel the following product ($\gamma_B = 833kgf/m^3$, $\nu_B = 7.6cSt$).

The records of sonic velocity $a(t_j)$ is graphically illustrated in Fig 2. This figure incorporates approximately 700 time instants; the value of N in the database.

Although not visible as a result of the ordinate scale adopted, small amplitude perturbations are present along the entire signal in Fig 2. Such perturbations are due to the hydraulic transients in the line and may be interpreted as random erros. This "noise" in the sonic signature register requires an elaboration of a procedure capable to accurately indentify the time interval $[t_o, t_l]$ in which sonic velocity is changing due to the mixture process only. The interface delimitation will be one of the subjects of the next section.

3. DATA REDUCTION PROCEDURE

The main objective of this section is to present the general procedure conceived to evaluate the mixing volume based on the acquired data reported in the past section. To

this end, we present below a step-by-step procedure:

1. Using the values of $a(t_j)$, $j = 1, \cdots, N$, it is determined the time instantes t_o and t_l, which characterize the mixture interface, as well as the values of a_A and a_B.

2. A correlation between a and C_B is proposed so that $C_B(t_j)$ can be evaluated based on $a(t_j)$ for $j = o, o + 1, \cdots, l - 1, l$, by noting that $C_B(t_o) = 0$ and $C_B(t_l) = 1$.

3. With $C_B(t_j)$, for $j = o, o + 1, \cdots, l - 1, l$, in one hand the pre-set values of the maximum admissible concentrations C_{AB} and C_{BA} at the other it is estimated the time instants t_{BA} and t_{AB}. Finally, with t_{BA}, t_{AB} and $Q(t_j)$, for $j = o, o+1, \cdots, l - 1, l$, it is evaluated a numerical approximation for V_c.

In the sequel, the aforementioned steps are decribed in detail.

3.1. Interface delimitation

If pressure and temperature conditions at the point the sonic velocity data is acquired were kept constants and also there were no perturbations in the process of data aquisition, then the sonic velocities $a_\imath$, with $\imath \in \{A, B\}$, as well as the time instants t_o and t_l would be promptly determined. In such a case, t_o would be equal to the greatest time instant of the set $\{t_j\}$, $j = 1, 2, \cdots, N$, for which $a(t_o) = a_A$. Analogously, t_l would be equal to the smallest time instant of the set $\{t_j\}$, $j = o + 1, 2, \cdots, N$, for which $a(t_l) = a_B$. Since the above conditions are not verified in practice, it becomes necessary to establish a mathematical criterion in order to determine t_o, t_l and $a_\imath$, with $\imath \in \{A, B\}$. To achieve this goal, the following statistical procedure is employed.

Consider two arbitrary time instants t_r and t_s, with $t_r \leq t_s$ of the set $\{t_j\}$, $j = 1, 2, \cdots, N$. Let $\bar{a}_A$ and $\bar{a}_B$ represent, respectively, the arithimetic mean of the sonic velocity samples $\{a(t_1), \cdots, a(t_r)\}$ and $\{a(t_s), \cdots, a(t_N)\}$, that is

$$\bar{a}_A = \frac{\sum_{j=1}^{r} a(t_j)}{r} \quad \text{and} \quad \bar{a}_B = \frac{\sum_{j=s}^{N} a(t_j)}{N - s + 1} \tag{5}$$

By assuming that the above sets represent observations of a multiple-sample experiment, the confidence interval $\bar{h}_\imath$ associated to the mean value $\bar{a}_\imath$, $\imath \in \{A, B\}$, can be expressed as (Moffat, 1988)

$$\bar{h}_A = Z_A \frac{S_A}{\sqrt{r}} \quad \text{and} \quad \bar{h}_B = Z_B \frac{S_B}{\sqrt{N - s + 1}} \tag{6}$$

in which $Z_\imath$, $\imath \in \{A, B\}$, is the Student's statistic appropriate for the number of samples and a confidence level desired (95% confidence in our case) and $S_\imath$, $\imath \in \{A, B\}$, is the standard deviation of these sets:

$$S_A = \left\{ \frac{\sum_{j=1}^{r} (a(t_j) - \bar{a}_A)^2}{r - 1} \right\}^{1/2} \quad \text{and} \quad S_B = \left\{ \frac{\sum_{j=s}^{N} (a(t_j) - \bar{a}_B)^2}{N - s} \right\}^{1/2}. \tag{7}$$

Based on the past definitions, we proposed that t_o and t_l be the time instants t_r and t_s, respectively, of the set $\{t_j\}$, $j = 1, 2, \cdots, N$ which verify the following properties:

1. the number of elements of the sequences $\{a(t_1), \cdots, a(t_r)\}$ and $\{a(t_s), \cdots, a(t_N)\}$
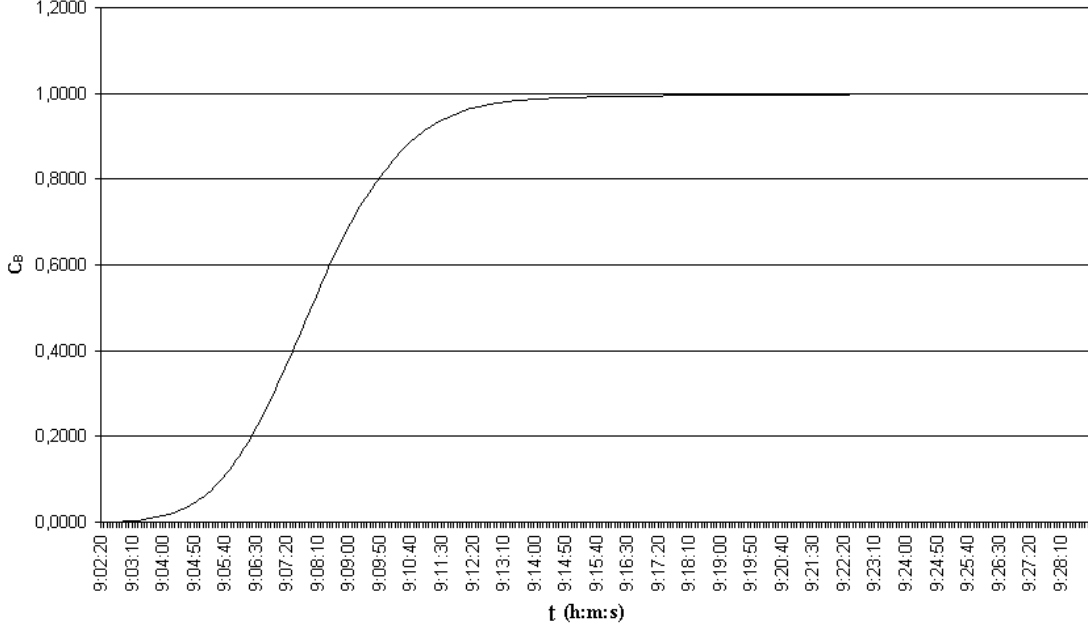
Figure 3: Concentration of fluid "B", C_B, as function of time at $x = 199.9 km$.

are maximized without excluding the intermediate ones;

2. the intervals of confidence $\bar{h}_\imath$, $\imath \in \{A, B\}$, defined in (6) are minimized.

Once the above algorithm is implemented (Freitas Rachid et al., 1999a), it provides the time instants t_o and t_l as well as the sonic velocities $a_\imath$, $\imath \in \{A, B\}$, of the following and leading fluids for a 100 % purity.

At the end of this step we have $o := r$, $l := s$ so that

$$a_A := \bar{a}_A, \qquad a_B := \bar{a}_B, \qquad h_A := \bar{h}_A \text{ and } h_B := \bar{h}_B. \tag{8}$$

3.2.   Concentration profile determination

In order to derive a correlation between the sonic velocity of the mixture and its concentration we recall that the wave propagation velocity under small disturbances in a unbounded liquid medium is given by (Wylie and Streeter, 1993)

$$a = \sqrt{\frac{K}{\rho}} \tag{9}$$

in which ρ stands for the density and K the isoentropic bulk modulus of the mixture. By denoting $\Delta V/V$ as being the volumetric deformation experimented by the mixture when submitted to a pressure variation Δp, the bulk modulus can be written as (Wylie and Streeter, 1993)

$$K = -\frac{\Delta p}{\Delta V/V} \tag{10}$$

For a binary mixture made up of imiscible liquids "A" and "B", whose densities and volumes are $\rho_\imath$ and $V_\imath$ with $\imath \in \{A, B\}$, the total volume of the mixture and its density

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can be expressed as:

$$V = V_A + V_B \tag{11}$$

$$\rho = \rho_A C_A + \rho_B C_B \tag{12}$$

in which C_i is the volumetric concentration of fluid i in the mixture.

If the bulk modulus of "A" and "B" are

$$K_i = -\frac{\Delta p}{\Delta V_i / V_i}, \tag{13}$$

the definition (10) along with (11) can be combined to express the bulk modulus of the mixture as:

$$K = \frac{K_A K_B}{K_A C_B + K_B C_A} \tag{14}$$

The sonic velocity of the mixture can be expressed as function of the volumetric concentration of fluid "B", C_B, by substituing (14) and (12) in (9):

$$a = \sqrt{\frac{a_A^2 a_B^2}{a_A^2 C_B^2 + (1 - C_B)C_B(r_{A/B}a_A^2 + r_{B/A}a_B^2) + a_B^2(1 - C_B)^2}} \tag{15}$$

with

$$r_{A/B} = \frac{\rho_A}{\rho_B} \qquad \text{and} \qquad r_{B/A} = \frac{1}{r_{A/B}} = \frac{\rho_B}{\rho_A}$$

Finally, when equation (15) is solved for C_B one gets, for $r_{A/B} \neq 1$ (or $r_{B/A} \neq 1$),

$$C_B = \begin{cases} \frac{1}{2\mathrm{C_{II}}}\left(\mathrm{C_I} + \sqrt{\mathrm{C_I^2} - 4\mathrm{C_{II}}\mathrm{C_{III}}}\right), & \text{if} \quad a_B \leq a \leq a_A \\ \frac{1}{2\mathrm{C_{II}}}\left(\mathrm{C_I} - \sqrt{\mathrm{C_I^2} - 4\mathrm{C_{II}}\mathrm{C_{III}}}\right), & \text{if} \quad a_B \geq a \geq a_A \end{cases} \tag{16}$$

and, for $r_{A/B} = 1$ (or $r_{B/A} = 1$):

$$C_B = \frac{\mathrm{C_{III}}}{(a_B^2 - a_A^2)}, \quad \text{if} \quad a_B \leq a \leq a_A \quad \text{or} \quad a_B \geq a \geq a_A \tag{17}$$

in which

$$\begin{aligned} \mathrm{C_I} &= (2 - r_{B/A})a_B^2 - r_{A/B}a_A^2 \\ \mathrm{C_{II}} &= (1 - r_{B/A})a_B^2 + (1 - r_{A/B})a_A^2 \\ \mathrm{C_{III}} &= a_B^2(a^2 - a_A^2)/a^2 \end{aligned}$$

Relationships (16) and (17) are systematically used to transform the sonic velocity data $a(t_j)$ into volumetric concentration $C_B(t_j)$ for $j = o, o+1, \cdots, l-1, l$. The concentration time history at the receiving point $C_B(t_j)$ is displayed in Fig 3.
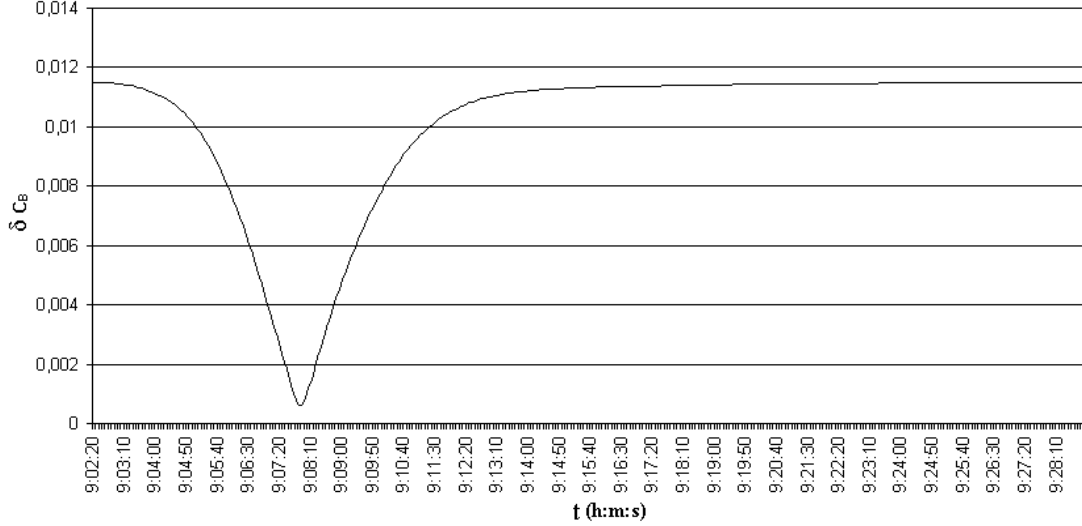
Figure 4: C_B uncertainty as function of time at $x = 199.9 km$.

3.3. Mixing volume computation

To compute the mixing volume it becomes necessary to numerically approximate the integral in (4). To do so, we have used the trapeziodal rule and have assumed that the time instants t_{BA} and t_{AB} (which define the begining and the end of the mixing region for a pre-set couple of admissible concentration C_{BA} and C_{AB}) are such that $t_{p-1} \leq t_{BA} \leq t_p$ and $t_k \leq t_{AB} \leq t_{k+1}$ with $\Delta t \ll t_{BA} - t_{AB}$. As a result, the mixing volume can be written as:

$$V_c = \int_{t_{BA}}^{t_p} Q(t)dt + \int_{t_p}^{t_k} Q(t)dt + \int_{t_k}^{t_{AB}} Q(t)dt =$$

$$\frac{\Delta t}{2}\Big[Q(t_p)(1 + 2\alpha_{BA} - \alpha_{BA}^2) + \alpha_{BA}^2 Q(t_{p-1}) + Q(t_k)(1 + 2\alpha_{AB} - \alpha_{AB}^2) +$$

$$\alpha_{AB}^2 Q(t_{k+1})\Big] + \Delta t \sum_{j=p+1}^{k-1} Q(t_j) + O(\Delta t^3) \tag{18}$$

in which α_{BA} and α_{AB} are determined from $C_B(t_j)$ by means of linear interpolations as:

$$\alpha_{BA} = \frac{C_B(t_p) - C_{BA}}{C_B(t_p) - C_B(t_{p-1})} \qquad ; \qquad \alpha_{AB} = \frac{1 - C_{AB} - C_B(t_k)}{C_B(t_{k+1}) - C_B(t_k)}$$

4. UNCERTAINTY ANALYSIS

In order to properly analize and compare the experimental data with available theoretical predictions, we next report the uncertainties of our experimental results.

4.1. Random and fixed errors

Let $\delta\rho$, δa_A, δa_B, δa and δQ represent the total error associated to the experimental measurements of ρ, a_A, a_B, $a(t_j)$ and $Q(t_j)$, for $j = o, o+1, \cdots, N$, respectively. As usual, we consider the total erros as being due to erros of fixed and random natures.

Fixed erros are those inhereted to the tolerances of the instruments and will be referred to as $\delta^f Q$, $\delta^f a$ and $\delta^f \rho$. Since a same instrument was used to measure a_A, a_B and a we have $\delta^f a = \delta^f a_A = \delta^f a_B$. According to the instrumentation used, we have $\delta^f Q = 0.05944 m^3/h$, $\delta^f a = 0.005 m/s$ and $\delta^f \rho = 0.0005 \rho^*$, where ρ^* is the water density at $4^o C$. Any other non-fixed errors are random. We refer to them as $\delta^r \rho$, $\delta^r a_A$, $\delta^r a_B$, $\delta^r a$ and $\delta^r Q$. In the present case, it seems reasonable to assume that random erros exist for the sonic velocities only, as a result of presssure transients in the line and temperature variations. In other words, we consider that $\delta^r \rho = 0 = \delta^r Q$.

On the other hand, based on the analysis reported on section 3.1, we promptly see that

$$\delta^r a_\imath = |h_\imath| \qquad \text{for} \qquad \imath \in \{A, B\} \tag{19}$$

In contrast to what happens to $a_\imath$, $\imath \in \{A, B\}$, for which multiple samples are available, only one measure is carried out for the sonic velocity of the mixture $a(t_j)$, for $t_j \in [t_o, t_l]$. Thus, we consider

$$\delta^r a = \max \{\delta^r a_A, \delta^r a_B\}$$

Finally, for each measurement the total error is computed by taking the square-root-sum of the fixed and random erros.

4.2. Concentration uncertainty

To compute the uncertainty associated to $C_B(t_j)$ we note through (16) or (17) that the correlation between C_B and a may be regarded as function of the following independent quantities $(a(t), a_A, a_B, r_{A/B})$. Thus, the uncertainty $\delta C_B(t_j)$ may be written as combination of the individual terms by a root-sum-square method (Moffat, 1988)

$$\delta C_B(t_j) = \sqrt{\left(\frac{\partial C_B}{\partial a} \delta a\right)^2 + \left(\frac{\partial C_B}{\partial a_A} \delta a_A\right)^2 + \left(\frac{\partial C_B}{\partial a_B} \delta a_B\right)^2 + \left(\frac{\partial C_B}{\partial r_{A/B}} \delta r_{A/B}\right)^2} \tag{20}$$

in which $\delta r_{A/B}$ is given by:

$$\delta r_{A/B} = \frac{\sqrt{(1 + r_{A/B}^2)}}{\rho_B} \delta \rho$$

It should be pointed out that $\delta C_B(t_j)$ depends on the time instant t_j through $a(t_j)$. As it will be seen later, we shall make use of $\delta C_B(t_j)$ in evaluating the uncertainty of the mixing volume.

4.3. Mixing volume uncertainty

The mixing volume uncertainty is also evaluated by using the root-sum-square method described in (Moffat, 1988). To achieve this goal, we first note that the mixing volume expression (4) can be regarded as a functional relationship of the form $V_c = V_c(t_{BA}, t_{AB}, Q(t))$ of independent arguments. By denoting the uncertainties associated to the time instants t_{BA} and t_{AB} as δt_{BA} and δt_{AB}, respectively, the uncertainty associated

to the mixing volume will be:

$$\delta V_c = \sqrt{\left(\frac{\partial V_c}{\partial t_{BA}}\delta t_{BA}\right)^2 + \left(\frac{\partial V_c}{\partial t_{AB}}\delta t_{AB}\right)^2 + \left(\frac{\partial V_c}{\partial Q(t)}\delta Q\right)^2} \qquad (21)$$

In the above equation, the partial derivatives represent the sensitivity coefficients of V_c with respect to the independent measurements and are given by

$$\frac{\partial V_c}{\partial t_{BA}} = -Q(t_{BA}), \qquad \frac{\partial V_c}{\partial t_{AB}} = Q(t_{AB}), \qquad \frac{\partial V_c}{\partial Q(t)} = t_{BA} - t_{AB}$$

To complete the evaluation of δV_c it remains to determine δt_{BA} and δt_{AB}. Since (16) or (17) associate one value of $C_B(t_j)$ to a single time instant $t_j \in [t_o, t_l]$, the uncertainty $\delta t(t_j)$, for $j = BA$ and $j = AB$ can be computed from $C_B(t_j)$ through the following relationships

$$\delta t_{BA} = \left(\frac{\partial C_B}{\partial t}\bigg]_{t_{BA}}\right)^{-1}\delta C_B(t_{BA}) \quad \text{and} \quad \delta t_{AB} = \left(\frac{\partial C_B}{\partial t}\bigg]_{t_{AB}}\right)^{-1}\delta C_B(t_{AB}) \qquad (22)$$

in which $\delta C_B(t_{BA})$ and $\delta C_B(t_{AB})$ are approximated by

$$\delta C_B(t_{BA}) = \delta C_B(t_p) - \alpha_{BA}[\delta C_B(t_p) - \delta C_B(t_{p-1})]$$

$$\delta C_B(t_{AB}) = \delta C_B(t_k) + \alpha_{AB}[\delta C_B(t_{k+1}) - \delta C_B(t_k)].$$

It should be noticed that we have used expression (4) instead of (18) in computing the uncertainty associated to the mixing volume. In other words, we have disregarded the numerical approximation error of order $O(\Delta t^3)$ as well as those inhereted to the linear interpolations.

5. RESULTS AND DISCUSSION

For the specific batch transfer reported at the end of section 2, the procedures outlined in section 3 give the following results: $a_A = 1201.81 m/s$, $\delta a_A = 0.0629 m/s$, $a_B = 1362.97 m/s$, $\delta a_B = 0.0114 m/s$, $t_o = 09:02:20$ and $t_l = 09:28:55$. The concentration uncertainty time history shown in Fig 4 presents a minimum at $t \approx 09:08:00$, in which $\delta C_B \approx 0.001$, and reach its maximum ($\delta C_B \approx 0.011$) at t_o and t_l.

To better understand the relationship between the mixing volume and interface points, mixing volumes were evaluated at the receiving point for different admissible concentrations $C_{AB} = C_{BA} = 1, 2, \ldots, 9, 10\%$. The results are depicted in Fig 5, which also displays the predictions of seven methods currently used to predict mixing volumes: Sjenitzer (1958), Austin and Palfrey (1964), Levenspiel (1958), Ovadi and Török (1977), Smith-Schulze (1948a, 1948b), Aunicky (1970) and Baptista et al. (2000).

Figure 5 reveals that mixing volume uncertainty is highly dependent on the choice of the interface points that define the start and finishing of the contaminated zone. Interface points for which $C_{AB} = C_{BA} \leq 1\%$ give rise to mixing volume uncertainties greater than 39%. For interface points of 3%-97% the mixing volume uncertainty is of 11%. However, this uncertainty is reduced to 5% if interface points of 5%-95% are used and can reach
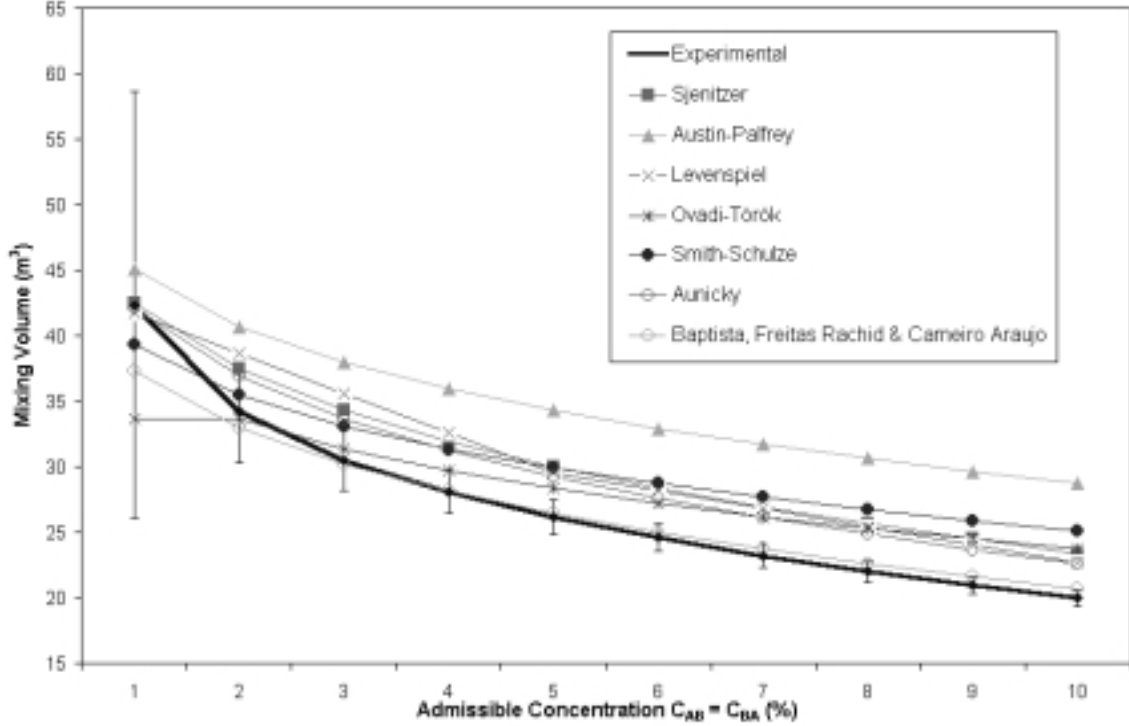
Figure 5: Predicted and measured mixing volumes as a function of admissible concentrations.

values as low as 3% when the range 10%-90% is considered. In summary, the less the admissible concentrations are, the greater the mixing volume uncertainty is. As it can be seen by inspecting equations (21) and (22), such a kind of behavior does not strongly depend on the accuracy of $\delta C_B(t_j)$ but on the intrinsic asymptotic nature of the curve $C_B(t_j)$ characterized by $\partial C_B/\partial t \to 0$ as $t \to t_o$ and $t \to t_l$.

In practical terms, no comparison among the seven methods can be effectively done for $C_{AB} = C_{BA} < 2\%$ inasmuch as their predictions falls within the experimental uncertainty.

6. CONCLUDING REMARKS

It has been presented a simple methodology to compute mixing volumes in batch transfers by registering the sonic signature of the fluids. Despite the high accuracy of the instrumentation used it is shown that mixing volumes should not be calculated nor reported based on interface points less than or equal to 1% - 99%. For this percentagem, the intrinsic nature of the concentration profile induces extremely high values of uncertainties, what certainly compromises any comparison among experimental and/or theoretical results.

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