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EVALUATING THE UNCERTAINTY IN THE MEASUREMENT OF CUMULATED VOLUME OF NATURAL GAS

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Abstract: An equation to obtain the uncertainty in the measurement of cumulated volume of natural gas by orifice plate meters and gas chromatography is proposed. Results depend mainly on the sampling rate of chemical properties and on the expected variations in natural gas composition. The method may serve to perform a cost-benefit study of implementing on-line gas chromatography analysis.

Keywords: measurement uncertainty, orifice plate meters, gas chromatography.

1. INTRODUCTION

In most commercial transactions, the sales price is ascertained by multiplying the unit price for a category of goods by the number of units delivered and accepted under some agreement. The amount of goods has to be measured, but the result involves always some uncertainty. As a result, both buyer and seller realize an unknown loss or profit. To mitigate the effects of this undesirable situation, the measurement uncertainty should be reduced as much as possible. However, this reduction is often achieved at the expense of factors that have an economic impact, such as costly equipment. Therefore, investments on better measuring systems should be compensated by the expected benefit of reducing the measurement uncertainty.

This problem does not usually arise in connection with day-to-day commercial measuring instruments such as supermarket balances, fuel dispensers or taxi meters, because their uncertainty is normally assumed to be low enough. For example, most of us would not care much, or would not even notice, if in paying for 1 kg of potatoes we actually brought home just 990 g. But since amounts involved in the trading of commodities are much larger, a closer look at the uncertainties in their measurement may be amply justified.

In the natural gas industry, the problem is particularly acute. As an illustration, consider the 50 million cubic meters pumped every day through the Brazilian pipelines. A meager 1% error in their measurement would produce an economic impact of some 28 million USD per year.

Typically, natural gas companies measure the volume by meters whose indications have to be corrected in accordance with the chemical composition of the gas. The latter is usually obtained from expensive gas chromatographs, so companies must decide on how many of these equipments to install and on how often to use them. Such decisions have a direct impact on capital and operating costs but also, though not so obviously, on the measurement uncertainty.

In this paper we develop a procedure to evaluate the uncertainty in the measurement of the volume of natural gas that passes through a given measuring station during some definite period of time. The facility is assumed to consist of an arrangement of orifice plates and a chromatograph connected to a flow computer. It is shown that the relative uncertainty depends strongly on the gas composition, and that it can be reduced by increasing the frequency of chemical analysis. These results can be of help in deciding the methods and equipment to be used for the measurement of natural gas.

2. THEORY

The volumetric flow rate at base conditions b (20 °C and 101.325 kPa) obtained from the readings of an orifice plate is given by the following well-known relation [1]:

$$\dot{Q}_\mathrm{b} = \frac{C\,\varepsilon}{\rho_\mathrm{b}} \frac{\pi d^2}{4} \left(\frac{2\rho_\mathrm{f}\,\Delta p}{1-\beta^4} \right)^{1/2} \qquad (1)$$

where C is the coefficient of discharge; ε is the expansion factor; d is the orifice plate bore diameter; β is the ratio d/D; D is the meter tube internal diameter; ρ is the gas density; Δp is the difference in static pressures taken at the orifice upstream and downstream taps and subscript f represents the flow conditions.

The density is determined by:

$$\rho = \frac{M\,p}{R\,T\,Z} \qquad (2)$$

where M is the molar mass of the gas; p is the absolute pressure; R is the universal gas constant; T is the absolute temperature and Z is the compressibility factor. Combination of (1) and (2) gives:

$$\dot{Q}_\mathrm{b} = F\, Z_\mathrm{b} \left(\frac{p_\mathrm{f}}{T_\mathrm{f}\, M\, Z_\mathrm{f}} \Delta p \right)^{1/2} \qquad (3)$$

where

$$F = C\sqrt{2R}\, \varepsilon \frac{\pi}{4} \frac{T_\mathrm{b}}{p_\mathrm{b}} \left(\frac{1}{d^4} - \frac{1}{D^4} \right)^{-1/2} . \qquad (4)$$

To obtain the cumulated gas volume over a specified integration time, *e.g.* one day, equation (3) must be integrated. Physical properties such as pressure and temperature are sampled at short time intervals Δt, but physicochemical properties necessary for the evaluation of Z_b, Z_f and M are measured less frequently through chromatography.

Typically, flow computers are configured to calculate flow rates for a fixed gas composition. This is then updated by the information obtained from a remote chromatograph which can be used to feed data to several flow meters, perhaps once a day. Alternatively, one chromatograph may be placed close to the meters, allowing for several on-line analyses to be carried out per day. This second option, however, calls for the presence, in the measurement station, of experts to operate and maintain the equipment, implying further investments and additional operational costs.

Whatever the chosen option, the integrated volume through the orifice plate can be expressed as [2]:

$$Q_\mathrm{b} = F\, \Delta t \sum_{j=1}^{J} Z_{\mathrm{b}j} \left(\frac{1}{M_j Z_{\mathrm{f}j}} \right)^{1/2} \sum_{i=1}^{I} \left(\frac{p_{\mathrm{f}ij}\, \Delta p_{ij}}{T_{\mathrm{f}ij}} \right)^{1/2} \qquad (5)$$

where I is the number of readings of temperature and pressure taken between each of the J measurements of composition during the integration time.

While in principle all quantities in equation (5) exhibit some degree of correlation, in practice references [1,3,4] allow them to be considered independently from each other. In accordance with the law of propagation of uncertainties [5], the relative standard uncertainty of Q_b is then obtained by the following relation:

$$u_Q^2 = u_C^2 + u_\varepsilon^2 + \left(\frac{2\beta^4}{1-\beta^4} \right)^2 u_D^2 + \left(\frac{2}{1-\beta^4} \right)^2 u_d^2 +$$

$$\frac{1}{J} \left(u_{Z_\mathrm{b}}^2 + \frac{1}{4} u_{Z_\mathrm{f}}^2 + \frac{1}{4} u_M^2 \right) + \frac{1}{4IJ} \left(u_{p_\mathrm{f}}^2 + u_{\Delta p}^2 + u_{T_\mathrm{f}}^2 \right) \qquad (6)$$

where all standard uncertainty on the right-hand side are relative, and where the period Δt, the constant R and the base conditions T_b and p_b have been considered as devoid of uncertainty. Note that the product IJ is a constant, equal to the total number of measurements of temperature and pressure in the integration time.

Meter stations usually have several orifice plates in parallel (figure 1), so the total cumulated volume becomes

$$Q_{\mathrm{b}T} = \sum_{k=1}^{K} Q_{\mathrm{b}k} \qquad (7)$$

where K is the number of runs. As flow pressure distributes uniformly among all meters, the flow speed across each of them is the same. This condition gives

$$\frac{Q_{\mathrm{b}k}}{A_k} = \text{const. for all } k \qquad (8)$$

where $A_k = \pi D_k^2 / 4$ is the cross sections of the duct where the k^{th} orifice plate is placed. Considering again all Q_k's to be independent, the relative uncertainty of the total cumulated volume is then obtained as the square root of

$$u_\mathrm{T}^2 = \sum_{k=1}^{K} \left(\frac{A_k}{A} \right)^2 u_{Qk}^2 \qquad (9)$$

where

$$A = \sum_{k=1}^{K} A_k \qquad (10)$$

and where the uncertainties u_{Qk} are given by equations similar to (6).

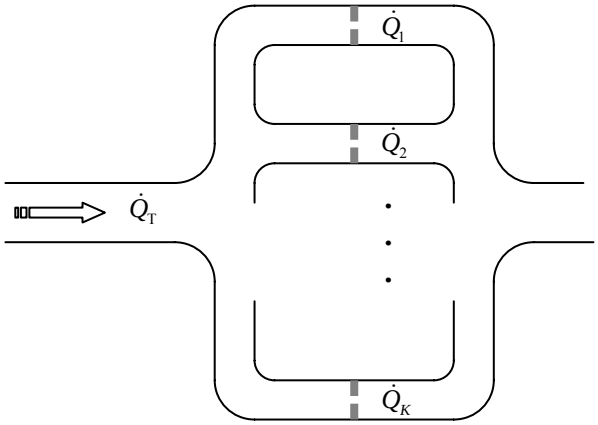

Fig. 1. Parallel arrangement of orifice plates.

3. EXAMPLE

Equations (6) and (9) were applied to evaluate the uncertainty in the measurement of the gas consumed by the Termopernambuco (TP) power plant, located in the State of Pernambuco, in the North-East coast of Brazil. The nominal consumption of this plant is 2.15 million cubic meters per day; it receives the gas from the processing units of either Pilar, in the State of Alagoas, or of Guamare, in the State of Rio Grande do Norte. The measuring station was constructed in compliance with the recommendations in [4]; it consists of $K = 4$ meter runs with the geometrical factors indicated in Table 1.

Recommendations to evaluate the standard uncertainty components in equation (6) are given in [3]; details can be found in [6]. The relative uncertainties corresponding to C,

ε, D, d, p_f, Δp and T_f are independent of the gas composition but depend on the flow conditions; these are shown in Table 2 for each meter run of the TP station. The relative uncertainties corresponding to Z_b, Z_f and M are shown in Table 3; they depend on the origin of the gas. The relative uncertainty of the molar mass for the gas coming from Pilar is much larger, due to its larger variations in chemical composition.

Table 1. Geometrical factors for the TP measuring station.

Factor	Meter run			
	1	2	3	4
β_k	0.5335	0.5276	0.3979	0.3956
A_k / A	36/74	36/74	1/74	1/74

Table 2. Relative standard uncertainty of quantities independent on composition for the TP measuring station (%)

Quantity	Meter run			
	1	2	3	4
C	0.45	0.45	0.56	0.56
ε	0.068	0.068	0.066	0.066
D	0.25	0.25	0.25	0.25
d	0.05	0.05	0.06	0.06
p_f	0.83	0.81	0.78	0.84
Δp	0.61	0.64	0.60	0.62
T_f	5.80	5.80	5.81	5.86

Table 3. Relative standard uncertainty of quantities independent on composition for the TP measuring station (%)

Quantity	Gas origin	
	Pilar	Guamare
Z_b	0.05	0.05
Z_f	0.20	0.21
M	6.08	1.04

Equation (6) was applied considering one day and $\Delta t = 1\,\text{s}$, so that $IJ = 86400$. As this large number gave a negligible contribution of the terms p_f, Δp and T_f, the factor $4IJ$ was ignored and the relative uncertainties in the measurement of these quantities was taken as equal to the repeatability of the respective instruments for the flow conditions in each meter run, as shown in Table 4. From this we conclude that sampling the physical variables every second, as recommended in [4], seems to be excessive, since no reduction occurs in the measurement uncertainty.

Table 4. Relative standard uncertainty of the last three terms in equation (6), for the TP measuring station, ignoring the factor $4IJ$ (%)

Quantity	Meter run			
	1	2	3	4
p_f	0.15	0.08	0.11	0.30
Δp	0.15	0.15	0.07	0.13
T_f	0.38	0.35	0.35	0.73

Figure 2 gives the final relative standard uncertainty u_T as a function of the number of chromatograph analysis per day, J, for each gas source. This figure shows that, if the gas composition exhibits strong variations, the measurement uncertainty can be drastically reduced.

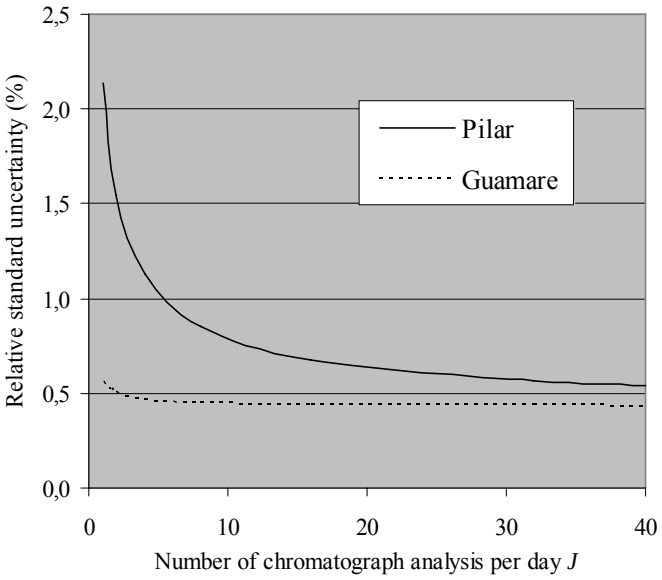

Fig. 2. Standard relative uncertainty of the total cumulated volume, in percent, as a function of the number *J* of chromatograph analysis per day.

It is also interesting to note that increasing the number of meter runs will always result in a decrease in the measurement uncertainty. As an illustration, assume that one additional meter run is added to the TP measuring station, with the same characteristics as those of meter 4. Figure 3 shows the percentage decrease in the standard uncertainty as a function of the number of chromatograph analysis per day, J, for each gas source. This figure shows that the decrease in standard uncertainty will be more pronounced the larger the variations in gas composition and the lesser the number of chromatograph analysis per day.

4. CONCLUSIONS

The main contribution of this paper is the development of equations (6) and (9) for evaluating the uncertainty in the measurement of cumulated volume of natural gas by orifice plates. These equations can easily be adapted to other types

of meters. They consider in particular the influence of the frequency of measurements of static pressure, differential pressure, temperature and chemical composition. They consider also the influence of the number of meters in the station. Until now, these factors were not addressed explicitly in related international document standards.

The analysis showed that the use of chromatograph-assisted gas flow measurement, in situations where the molar mass exhibits considerable variations, is an effective way of enhancing the overall performance of the measuring system, since the measurement uncertainty can then be reduced significantly. Depending on the total volume passing through the measurement station, the economic impact of this reduction in uncertainty may be substantial.

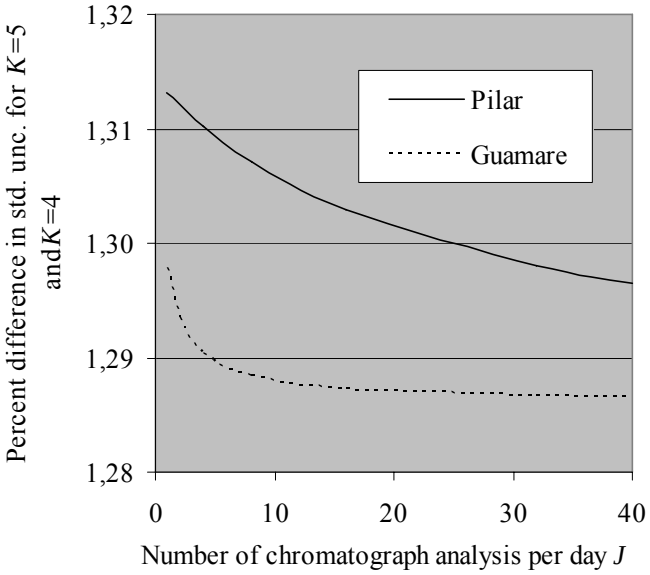

Fig. 3. Percent decrease in standard relative uncertainty if a meter run is added to the measuring station.

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