UNCERTAINTY AND REPRODUCIBILITY ANALYSIS OF A LABORATORIAL SCALED PIPE PROVER

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Abstract. *The work uses a laboratory scaled prototype of primary pipe prover flowmeter in order to assess conformity with the requirements established by technical standards and examine the uncertainties of flow measurement performed, besides to check the reproducibility, the influence of operating parameters such as operating pressure variation and comparison with gravimetric test. The prototype is plastic made tubing and considering statically defined dimensions. Inside tubing, an interfering elastomer sphere is driven by flow provided by a centrifugal pump. The detection system uses infrared light sensors able to detect the spheres passage causing any pipeline interference or blockage. The acquisition data system is automatic and records the sphere transit time through each pulse signal detected as well as the pulses generated by a calibrated turbine meter, as comparison of the evaluation of process uncertainties.*

Keywords: *pipe prover, uncertainty, flow measurement, gravimetric method, reproducibility, primary meter.*

1. INTRODUCTION

In petroleum industry, the custody transfer operations are characterized by the ownership transfer of an oil company to another in terms of contract following the technical requirements for fiscal measurement, which consists in measuring the produced volume by a accredited measuring point production (ANP, 2000). In such transactions, researches for improvements in measurement systems are essential because of the high capital values and taxes involved.

The standards API MPMS 4.2 (1988) and ISO 7278-2 (1988) establish that the flow meters used for custody transfer should be calibrated periodically. In turn, the Brazilian National Agency of Petroleum, Natural Gas and Biofuels - ANP, by its resolution n^o. 1 (ANP, 2000) regulates the calibration of measurement systems in line, which includes provers, master meters and other meters previously approved.

The bidirectional pipe prover is a prover type for primary flow checking. According to the Guide to Uncertainty of Measurement - GUM (2003), a prover of primary flow means that it is capable to estimate the flow rate through independent variables, in other words, direct relationship between volume and time, while a secondary flow prover does not correlate these variables directly, requiring intermediate correlations between physical properties of flow, such as coriolis, ultrasonic, orifice plate or electromagnetic flow meters.

So, the objective of this work is to analyze the uncertainty of flow measurement performed by a laboratory scaled pipe prover prototype in order to better understand the behavior of flow uncertainties in relation to specific standards, beyond the influence of operational parameters such as variation of operating pressure and comparison with gravimetric test as well as test the infrared sphere detection system.

2. BIBLIOGRAPHICAL REVIEW

One of the first pipe prover record is found in 1950, but using a cleaner pig as displacer. After soon the Shell Development Company used the sphere as displacer (Dobesh, 1983). According to Pfrehm (1962), before the development of such provers, the calibration was done by tank provers or master meters.

Redilla (1977) detailed the construction of unidirectional and bidirectional provers. Two years later, Su (1979) made several tests to determine statically what would be the minimum number of runs needed for a meter calibration under a desired confidence level.

Gyory (1984) compared, using the bidirectional prover, the rules of three entities: Physikalisch-Technische Bundesanstalt - PTB of Germany, National Office Measures Hungary - OMH and American Petroleum Institute - API, even before an international agreement for calibration and expression of uncertainty.

Comstock (1985) studied the usual methods of provers calibration in lines, the method of water draw and the master meter. In 1990, the author studied the interpolation pulses by three methods more usual: quadruple timing method, phase locked loop method and the double timing method (Comstock, 1990). Ten years of technological advances were reported by Jakubenas (1995). According to the author, these advances enabled the pipe prover greater reliability and accuracy of data in addition to reducing the cost of the prover.

Garcia and Sherief (1999) studied about the methodology used for calibration using the water draw method.

Silva (2004) studied the concepts and calculation procedures for uncertainty and its propagation, determination and classification. The author also presented some types of meters and made some considerations about the respective ways for calculating the uncertainty expressions. In turn, Ribeiro (2010) reports and computes correctly the uncertainty of a meter and discusses the calibration errors.

Lavezzo (2010) designed and built a laboratory pipe prover prototype in order to assess its experimental uncertainty and performance, fulfill the requirements established by the rules.

3. DESIGN OF PIPE PROVER

The main pieces of the pipe prover are sketched in Fig. 1. The prover consists of a U-form plastic pipe, 53 mm internal diameter and 9 m in length, equipped with four pairs of infrared transmitter/receptor sensors spaced 3 m each other. The system is completed with valves, tank, electrical centrifugal pump, flowmeter turbine type and a special arrangement for a four-way valve operation. But the equipment was dismantled during a civil works in the lab where it is installed, leading to the need to test its reproducibility after its reassembly.

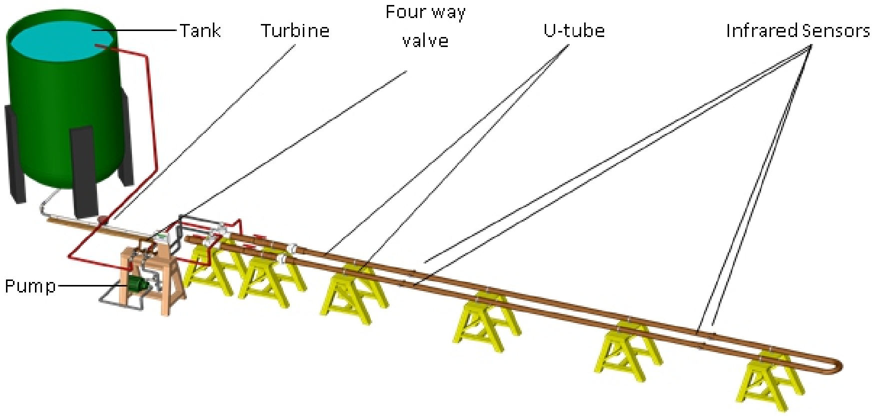


Figure 1. Pipe prover basic scheme and main parts.

For the measurements, it is used an interfering elastomer sphere which travels inside the pipe. Its interference should be about 2% larger than the inner pipe diameter, which is filled with the working fluid. This feature guarantees the tightness of the sphere even in motion avoiding errors of measurement, as provided by standard ISO 7278-2 (1988). A centrifugal pump drive the flow which propels the sphere inside the tube at a constant flow velocity. The automatic data acquisition system is automatic designed and constructed specifically for this application and it is composed of four pairs of transmitter-receiver sensors of infrared light, installed on the tubing external wall, preventing pipe blockage and interference in sphere movement, as shown in Fig. 2.

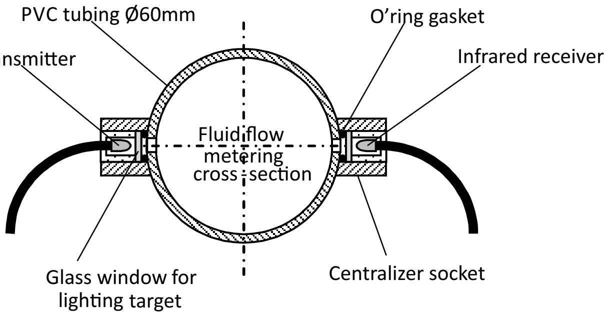
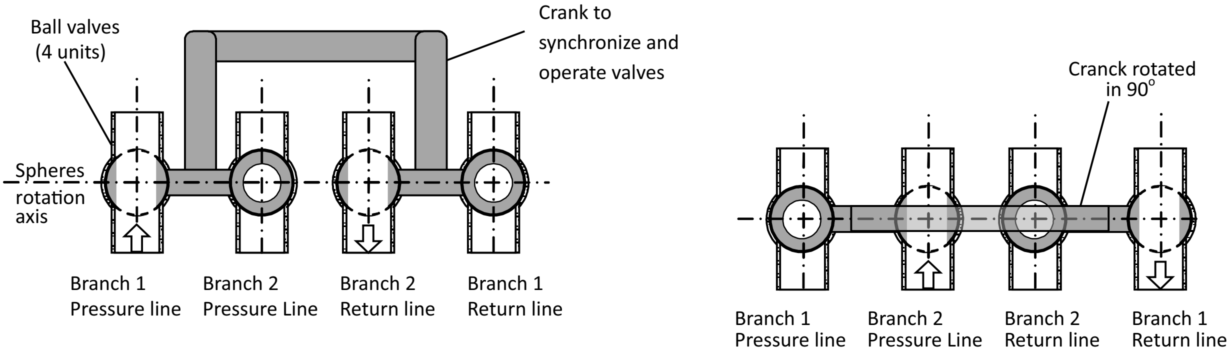


Figure 2. Detail of pipe prover cross section at infrared sensor system position, showing no interference on fluid flow Pipe prover basic scheme and main parts (Lavezzo, 2010).

Data acquisition system records the sphere transit time through each pulse signal detected at distances, as well as the pulses generated by the turbine meter.

Aiming flow reversion, ISO 7278-4 (1999) states the use of a four-way valve or a system of four valves working in a special arrangement. The latter was installed in the prototype due its lower costs (Lavezzo, 2010).

The valve system used consists of four ball valves connected in pairs, and operated in parallel by a crank, in such way that provide the flow reversion inside the U-tube, as shown in Fig. 3.



(a) (b)

Figure 3. Top view sketch of four-way valve assembly, showing two operational positions (Lavezzo, 2010):
Position (a): Pressure on branch 1 and return flow by branch 2;
Position (b): Pressure on branch 2 and return flow by branch 1.

4. BASE VOLUME

The pipe diameter is obtained by measurement with calibrated instruments. To measure the length between the sensors it is used a tape laser and, in order to determining the length statically, many measurements were performed. Thus, the base volume was calculated between the sensors (Lavezzo, 2010).

To calibrate the pipe prover base volume, it is used the gravimetric weighing method (ISO 4185, 1980), which consists in moving the sphere between the sensors pair, while the fluid is diverted into a container installed on a balance. At the operation end, it is recorded transit time, temperature, mass and fluid density accumulated in the container. According to Young (2009), this method was adopted by the National Institute of Standards and Technology (NIST) since 1997 and in 2003 the National Institute of Metrology, Quality and Technology (INMETRO) approved the norms NIE-DIMEL-043 (2003) and NIE-DIMEL-045 (2003) concerning to the gravimetric method.

5. OPERATION

The operation begins by inserting the sphere in the launcher with the four valves system arranged so that the flow inside the pipe is in opposite direction of launching the sphere. Then turns on the pump in order to initiate the flow until equalize the temperature of the system.

Once prover temperature is equalized, the four-valve system crank is actuated to change the flow direction. The sphere will accelerate at the beginning of the metering section in order to accelerate until reaches the uniform motion, in clockwise direction, passing through the series of four optical sensors, blocking the light detection and triggering the start of timing pulses. Flow through turbine is recorded as well.

To reverse the flow direction, the crank should be actuated starting a new transit time cycle, now in the Counterclockwise direction. After a few runs, the flow rate and its uncertainty are calculated statistically from the data obtained.

One of the advantages of bidirectional pipe prover consist to allowed the evaluation and estimation of hysteresis errors by the time records in clockwise (outward) and counterclockwise (return) directions.

6. UNCERTAINTIES EVALUATIONS

According to GUM (2003) there are two uncertainty type, that can evaluated with statistic (Type A) and other evaluated with experience or calibration certificate (Type B). In this work, the uncertainties are considered type A, so the uncertainties are obtained from a frequency distributions where the best available estimate of the expected value of a quantity that varies randomly and for which n independent observations $(x_{i,k})$ have been obtained under the same conditions of measurement, is the average $\overline{x}$ of the n observations, demonstrated in Eq. (1):

$$\bar{x}_i = \frac{1}{n}\sum_{k=1}^{n} x_{i,k} \tag{1}$$

Then the measurand may be given by $X_i = \bar{x}_i \pm \Delta x_i$, so a good estimative of X_i is represented by $\bar{x}_i$ with a variations $x_{i,k}$ that, due to random effects, its experimental variance has to be defined by Eq. (2):

$$s^2\left(x_{i,k}\right) = \frac{1}{n-1}\sum_{k=1}^{n}\left(x_{i,k} - \overline{x}_i\right)^2 \tag{2}$$

The uncertainty that represent the variations x_k, in average, will be the square root the experimental variance $x^2\left(x_{i,k}\right)$ divided by *n* observations as is the Eq. (3) (GUM, 2003):

$$u^2\left(\overline{x}_i\right) = s^2\left(\overline{x}_i\right) = \frac{s^2\left(x_{i,k}\right)}{n} \tag{3}$$

In order to determine the uncertainty of each variable that defines the flow, it is necessary to combine each result according to the mathematical relationship that define the measurand. Ribeiro (2010) suggest basic rules for the uncertainty propagation, which simplifies the calculations and does not require the partial derivatives use:

- In addition and subtraction operations, the uncertainties are propagated by the sum of absolute uncertainty or standard uncertainty.

$$u_c = \sqrt{\sum u(x_i)^2} \tag{4}$$

- In multiplication and division operations, the uncertainties are propagated by the sum of the relative uncertainties.

$$\frac{u_c}{\sum \overline{x}_i} = \sqrt{\sum\left(\frac{u\left(x_i\right)}{\overline{x}_i}\right)^2} \tag{5}$$

Although the combined standard uncertainty can be used to express the uncertainty of a measurement result in some commercial, industrial or regulatory sense, it is often necessary to report the uncertainty estimative as an interval around the measurement result which is expected to cover a large fraction of the distribution of values that could reasonably be attributed to the measurand. Then, an expanded uncertainty is obtained by multiplying the combined standard uncertainty by a correct factor t-student.

$$U = t\left(\nu\right) \times u_c\left(y\right) \tag{6}$$

Where, ν is degrees of freedom obtained by $\nu = n - 1$ with confidence interval, which can be obtained the correction factor t-student using the appropriate table (see GUM (2003)).

So the combined uncertainty relative to test the prover reproducibility and pressure variation effects will be composed by the combined uncertainty of thermal expansion - $u_c(\Delta V_T)$ - and prover pressure - $u_c \Delta V_P$, transit time - $u_c(t)$ - and the measured volume basis - $u_c(V_b)$, as demonstrated in the equation below:

$$u_c\left(y\right) = \sqrt{\left(\frac{u_c\left(t\right)}{\overline{t}}\right)^2 + \left(\frac{u_c\left(V_b\right)}{\overline{V_b}}\right)^2 + \left(\frac{u_c\left(\Delta V_T\right)}{\overline{V_b}}\right)^2 + \left(\frac{u_c\left(\Delta V_P\right)}{\overline{V_b}}\right)^2} \tag{7}$$

And for the gravimetric method, the combined uncertainty relative is compounded by the mass measurement - $u_c(M)$ - and the three-way valve - $u_c(M_{V3V})$, as in Eq. (8).

$$u_c\left(y\right) = \sqrt{\left(\frac{u_c\left(M\right)}{\overline{M}}\right)^2 + \left(\frac{u_c\left(M_{V3V}\right)}{\overline{M}}\right)^2} \tag{8}$$

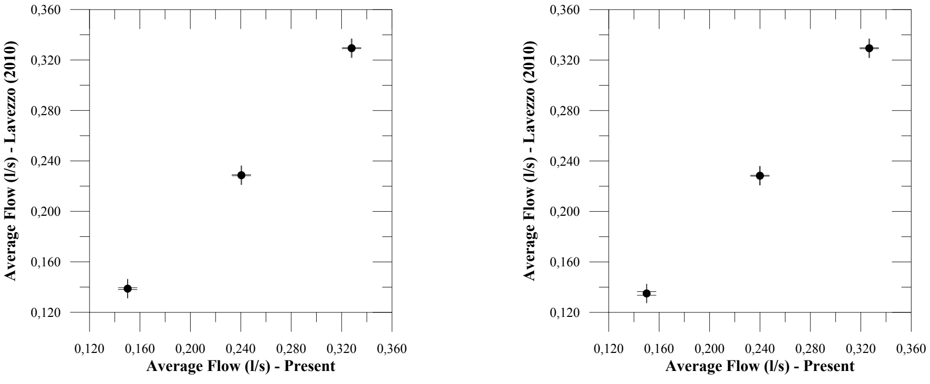
7. RESULTS AND DISCUSSION

One objective of this work is to certify the system reproducibility after the reassembly of the pipe prover. Thus this work follows the procedures adopted by Lavezzo (2010), which uses twenty cycles (corresponds to a run-way and another back in the prover) in three levels of flow (maximum, intermediate and minimum).

It adopted the rejection criterion of Chauvenet, according to Mendes and Rosario (2005), which determines the magnitude of the deviation d_i of a particular measurement x_i if the average is greater than a value d_{ch} (limit rejection of Chauvenet) the measurement should be rejected.

7.1 Reproducibility

After applying the criterion of rejection, the results obtained will be compared with data from Lavezzo (2010). These will be presented in graphs with three levels of flow combined with their absolute uncertainties, as can be seen in Fig. 4.



(a) Clockwise Direction

(b) Counter Clockwise Direction

Figure 4. Comparing data for reproducibility test.

Tab. 1 show the analysis numerically, since it is difficult to observe the uncertainties traces at the graph.

Table 1. Comparison data for reproducibility test.

		Present Work			**Lavezzo (2010)**		
Direction	**Level Flow**	**Average Flow (l/s)**	**Uncertainty Absolute (l/s)**	**Uncertainty Relative (%)**	**Average Flow (l/s)**	**Uncertainty Absolute (l/s)**	**Uncertainty Relative (%)**
Clockwise	**Maximum**	0,328	0,0003	0,10	0,329	0,0003	0,11
	Intermediate	0,240	0,0002	0,09	0,229	0,0004	0,16
	Minimum	0,150	0,0001	0,10	0,139	0,0007	0,53
Counter Clockwise	**Maximum**	0,327	0,0003	0,10	0,329	0,0004	0,10
	Intermediate	0,240	0,0002	0,09	0,228	0,0004	0,18
	Minimum	0,150	0,0001	0,10	0,135	0,0015	1,08
Complete Cycle	**Maximum**	0,327	0,0002	0,05	0,330	0,0004	0,12
	Intermediate	0,240	0,0001	0,04	0,228	0,0003	0,13
	Minimum	0,150	0,0001	0,04	0,142	0,0002	0,17

As can be observed in the Fig. 4 and Tab. 1, the flow rates approached those used by Lavezzo (2010), and these differences were due to different operators, while the combined uncertainty absolute behaves similarly and should only be attempted for the minimum flows than in previous work have an absolute uncertainty larger than the current one. The differences observed may be related to the fact that this job has a greater concern with impurities that can pass to the prover, thinking about it, a filter was installed between the tank and the turbine, thereby retaining the impurities that can be carried by the pump and taken to the prover. To ensure the efficiency of the filter is adopted the procedure to check and clean it at the beginning of each experiment.

The ISO standard 7278-2 (1988) states that the bidirectional pipe prover uncertainty of three runs should be 0,02%. Observing the Tab. 1, the relative uncertainties the current work are shown higher than established by norm and stable when compared to the uncertainties obtained by Lavezzo (2010).

7.2 Gravimetric Method

According to Lavezzo (2010), as described in section 4. , the prover base volume has 19,85 liters with combined absolute uncertainty the 0,02 liters. The applying results the gravimetric method can be seen in Fig. 5 it is noted that the volumes does not present the same values, considering clockwise direction (19.86 liters) and counter clockwise direction volume varies significantly with the level of flow set.

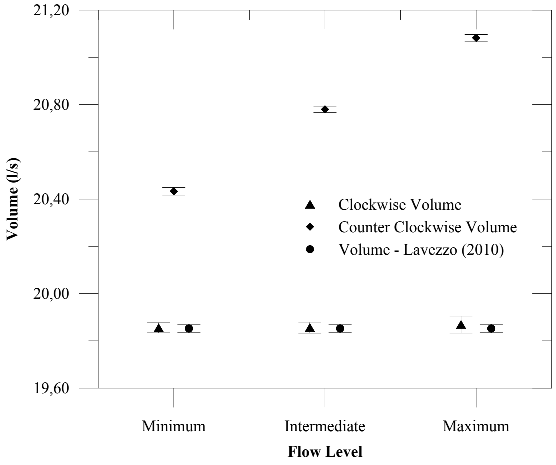


Figure 5. Data obtained from the gravimetric method.

Table 2. Gravimetric Method Results.

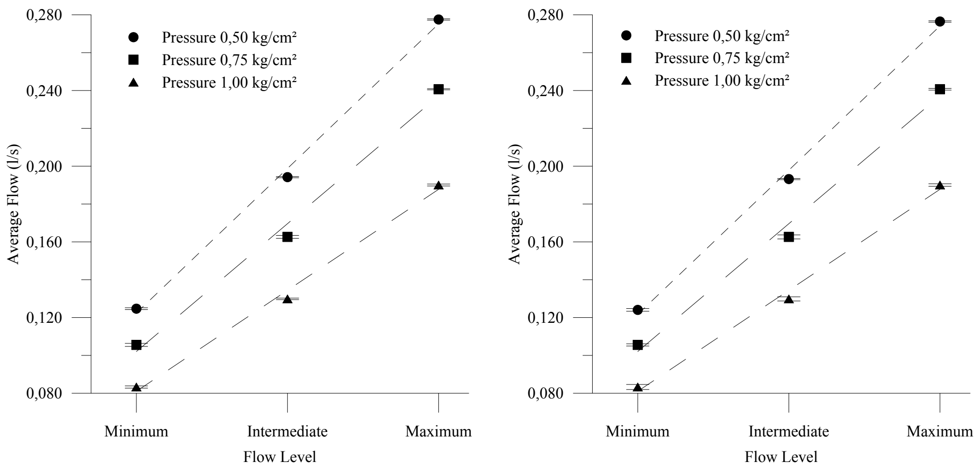
Flow Level	**Clockwise Direction** **Average Volume** (l)	 **Uncertainty Absolute** (l)	 **Uncertainty Relative** (%)	**Counterclockwise Direction** **Average Volume** (l)	 **Uncertainty Absolute** (l)	 **Uncertainty Relative** (%)
Maximum	19,87	0,0360	0,18	21,08	0,0142	0,07
Intermediate	19,86	0,0233	0,12	20,78	0,0137	0,07
Minimum	19,86	0,0212	0,11	20,43	0,0161	0,08

7.3 Pressure Test

For the pressure test it was used three pressure levels (0,50 , 0,75 and 1,00 kg/cm^2) and for each pressure is performed for three levels of flow (minimum, intermediate and maximum). As can be seen in Fig. 6, the average flow decrease as pressure increase, as expected, and the uncertainty increase.

Table 3. Experimental average data for test pressure.

Pressure (kg/cm^2)	**Flow Level**	**Clockwise Direction** **Average Flow** (l/s)	 **Uncertainty Absolute** (l/s)	 **Uncertainty Relative** (%)	**Counter Clockwise Direction** **Average Flow** (l/s)	 **Uncertainty Absolute** (l/s)	 **Uncertainty Relative** (%)
0,50	**Maximum**	0,278	0,0003	0,12	0,276	0,0004	0,13
	Intermediate	0,194	0,0003	0,16	0,193	0,0003	0,16
	Minimum	0,125	0,0005	0,39	0,124	0,0007	0,58
0,75	**Maximum**	0,242	0,0003	0,13	0,241	0,0005	0,19
	Intermediate	0,165	0,0008	0,47	0,163	0,0011	0,65
	Minimum	0,107	0,0008	0,76	0,106	0,0006	0,54
1,00	**Maximum**	0,189	0,0005	0,27	0,190	0,0007	0,35
	Intermediate	0,130	0,0004	0,32	0,130	0,0011	0,84
	Minimum	0,084	0,0006	0,70	0,083	0,0013	1,60



(a) Clockwise Direction (b) Counter Clockwise Direction

Figure 6. Experimental average data for test pressure.

8. CONCLUSION

Lavezzo (2010) through experiments proved that the bidirectional pipe prover had repeatability, and this work continuing to study and confirms the prover reproducibility. Despite the uncertainties are above the established by the standard they remained stable independently of the flow level.

The gravimetric method, showed that the prover base volume at the counter clockwise direction varies with the flow level and also differ the base volume in clockwise direction. The values are closes to Lavezzo (2010). The standard API MPMS 4.9.4 (2010) recommends that the repeatability of the gravimetric method is 0.02%, so the uncertainties obtained in the experiment were higher than recommended by the standard, this difference may be related to the fact that the diverter valve be operated manually, leading to increase the uncertainty.

For pressure test, the pressure incresing causes a linear increment in flow as well as the associated relative uncertainties overcoming the values recommended by ISO 7278-2 (1988).

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