EXPERIMENTAL ANALYSIS AND UNCERTAINTY EVALUATION OF LOW FLOWS RATES MEASUREMENTS BY PIPE PROVER

Rogério Ramos, ramosrogerio@hotmail.com
Márcio Coelho de Mattos, mcoelho@npd.ufes.br
Luís Fernando de Queiroz Lavezzo, luislavezzo@yahoo.com.br
Marcelo Protasio Kominsky, marcelokos@hotmail.com
Universidade Federal do Espírito Santo - UFES
Programa de Pós-Graduação em Engenharia Mecânica - PPGEM
Av. Fernando Ferrari, 514 Campus Universitário de Goiabeiras, Vitória, ES, CEP 29075-910

Abstract. *This work presents a project, in laboratorial scale of a pipe prover prototype and its experimental performance evaluation, aiming to assess the conformity to requirements established by technical norms, considering the measurement uncertainties and the contribution of distinct travel distances. Such pipe prover is composed by a plastic tube with dimensions statistically defined, in which an interfering elastomeric sphere travels driven by a centrifugal pump. Traveling time is automatically measured by an infrared sensor system specially design for this purpose. Such light sensor assembly is capable to detect the ball without any contact and so, any interference in its movement, unlike more usual electromechanical interrupters utilized in industrial applications. The paper is dedicated to the study of reference measurement of clear liquids at low flows in order to deal with some peculiarities related to the subject, which reach great importance in commercial transactions involving typical interests of petrochemical industry. Such variables include aspects such as constructive features of the meter, fluid properties, environmental conditions and operator ability, for instance. The estimated uncertainty for such device, about 0,02%, comply with that proposed by related technical norms. Furthermore, it is performed a comparison with a turbine meter previously calibrated by the manufacturer. Differences between measurements were estimated around 0,003 to 0,36%, depending on flow level.*

Keywords*: flow measurement, pipe prover, uncertainty, primary prover*

1. INTRODUCTION

In oil industry, custody transfer is a commercial transaction where some company responsible by an oil well explotation transfers the responsibility of a certain amount of exploited fluid from an operator to another, aiming transport by ducts or shipment. The high value usually associated to such flows and the governmental interest about taxes and tributes leads to a continuous improvement of measurement techniques in order to ensure its quality.

Technical norms and standards (API MPMS 4.2, 1988, ISO-7278-2, 1988) establishes that flowmeters, used to custody transfer operations, must have its performance verified at certain periods of time. This process is called flowmeter calibration and its objective is to prove with some confidence, the fluid quantity involved at each transfer operation. Brazilian legislation about this subject settle as qualified calibration systems for inline flowmeters: provers, tanks, master meters or other systems previously approved by Agência Nacional de Petróleo, Gás Natural e Biocombustíveis – ANP (ANP/INMETRO,2000)

Bi-directional pipe prover is a primary flow prover type (simply called pipe prover in this text) used to prove large volumes flowing in custody transfer operations (Tombs, 2006). In this context, the expression “primary flow” consist in obtain volume flow from independent and fundamentals variables expressed in the Guide of Uncertainty Measurement – GUM. Such variables should reach highest metrological quality, recognized without any allusion to other standards of same nature (GUM, 1995).

In this way, pipe prover device measure traveling time of an interfering elastomeric sphere when it is driven inside a determined length of duct. Volume flow measurement is obtained by direct ratio of known volume by registered period of time.

On the other hand, secondary flow meters do not correlate volume by time directly, needing an intermediary correlation. Examples of secondary flow meters are: turbines, rotameters, ultrasonic, coriolis and optical devices, each of them presenting a characteristic level of uncertainty on its readings and should be calibrated at defined period of time, in order to check and guarantee its performance.

The objective of this work is to analyze the uncertainties of flow metering performed by a prototype of pipe prover in laboratorial scale. A turbine performance is compared against pipe prover readings, as well.

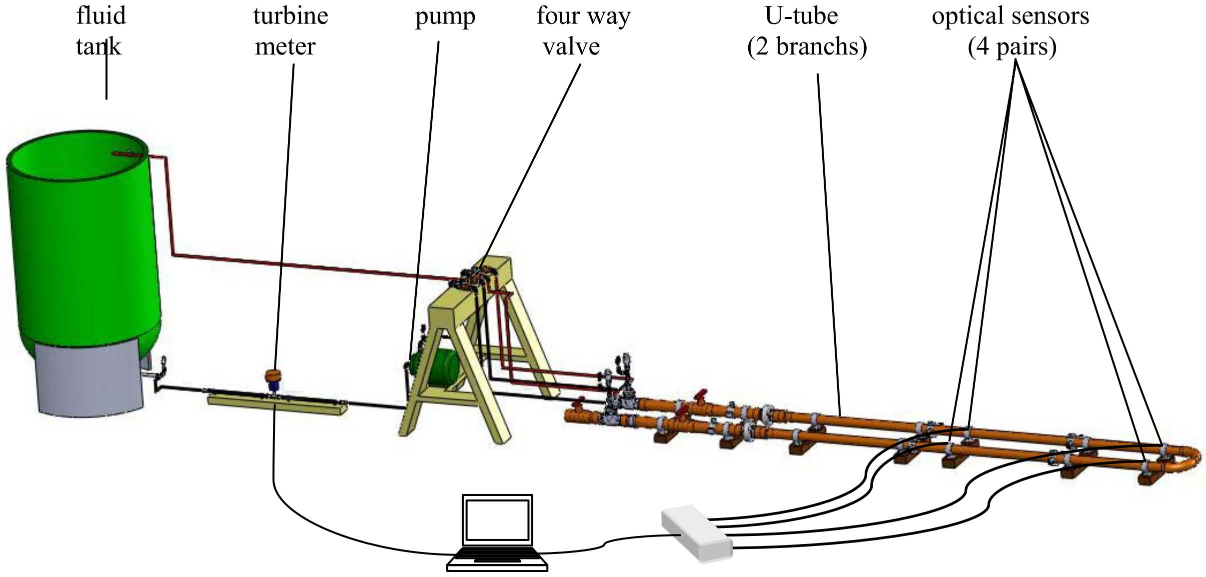
The pipe prover designed and assembled by the research team is directional type and it is evaluated in order to answer questions like:

- Is it enough the number of cycles proposed by norm (ISO-7278-2, 1988) in order to reach established uncertainty limits?
- Do shorter ducts lengths satisfy established uncertainty limits?

- Is there some trend on readings at any direction of travel?
- What are flow limits to operate pipe prover considering uncertainties?
- Is the turbine k-factor, provided by the manufacturer, in accordance to such primary prover?

2. PIPE PROVER PROJECT: DESIGN AND OPERATION

The laboratorial pipe prover is composed by a U-format tube Ø60mm and 6m of length each branch, made in welded PVC, Figs. 1a,b. Four pairs of optical infrared sensors are installed on this tube, equally spaced at 3m one to each other. In order to estimate its uncertainties, each distance is statistically evaluated.



(a)

(b)

Figure 1 – (a) Pipe prover basic scheme and main parts; (b) pipe prover assembled at laboratory

An interfering sphere, made by elastomeric matter and filled with work fluid, travels inside tube driven by a centrifugal pump. Following ISO-7278-2, 1988 recommendations, it is used a sphere with interference of 2% in diameter in order to not allow leakage between ball and internal tube wall and so, sphere should travels at same velocity of flow.

Automatic time data acquisition system, especially design for this application, consists in four transducer-receptor pairs of infrared light, assembled on tube external wall as demonstrated in Fig. 2.

Light sensor assembly is capable to detect sphere passage without any contact and so, any interference on its movement unlike more usual electromechanical interrupters typical of industrial applications, as can be seen in Fig.2. Each detection is registered by an electronic board. Travel time is computed for each sensor at each direction: clockwise and counterclockwise.

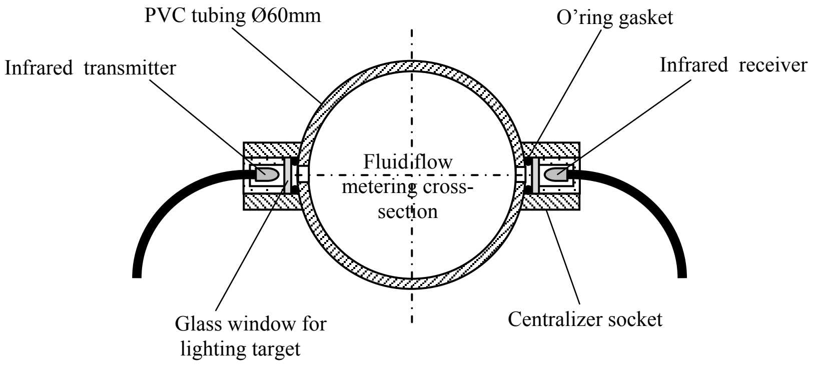
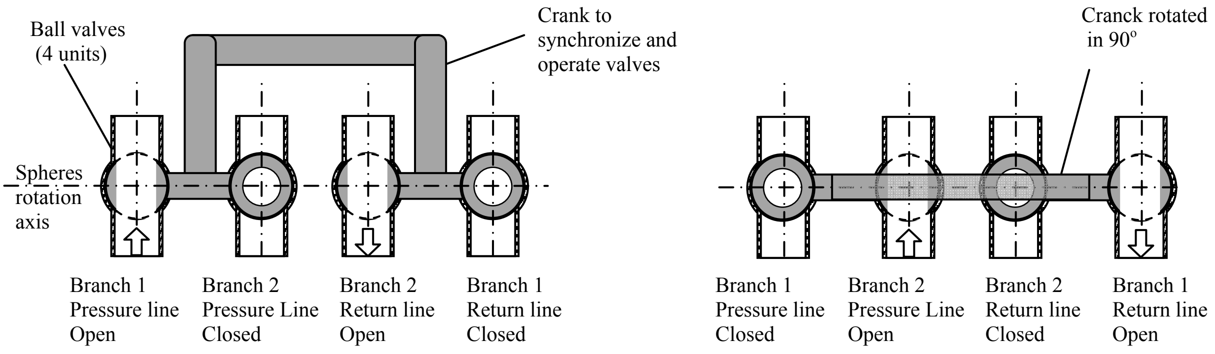


Figure 2 – Detail of pipe prover cross section at infrared sensor system position, showing no interference on fluid flow

Ball travel direction is determined by the position of a four-way valve, installed downstream from the pump. A special arrangement was designed for this purpose, in order to reduce costs since a four-way valve is expensive by nature.

In such way, four ordinary ball valves were assembled with their axis at horizontal direction and connected in pairs by a manual crank in order to operate in parallel, reversing flow inside U-tube, as indicated by Fig. 3.



(a) (b)

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

Once elastomeric sphere is placed inside U-tube at beginning of any branch and four-way valve is positioned to the desired direction, pump is turned on and sphere starts its travel.

At any branch, sphere movement is accelerated in an initial straight section from velocity zero to a uniform motion. Once such regime is reached, the ball passes in front of the first optical sensor, obstructing light detection and initiating a counter time cycle. Travel velocity depends on volume flow.

Sequentially, ball passes in front of next three sensors; each lighting obstruction has its time registered respectively by automatic acquisition data system until the sphere reaches the end of U-tube. In this situation, four-way valve is switched to another position, flow is reversed and a new cycle time count starts, but now in opposite direction. Such bi-directional travel procedure turns possible the estimation of some biased behavior.

After some time count cycles, volume flow can be statistically calculated and its stability and uncertainty may be evaluated.

A turbine meter is installed upstream of this arrangement, just after tank, for comparison reasons. At each infrared sensor position, readings of number of pulses and flow from turbine are registered as well. The results from pipe prover may be compared to such data, after statistical analysis.

Details of pipe prover assembly can be found in Lavezzo (2010).

3. UNCERTAINTIES EVALUATION

The uncertainty associated to a measurement reflects the lack of the accurate knowledge of the true value of a measurand. So, to decide whether a measurement system is suitable, the experimental variability of its measurements are often compared to the expected standard deviation, obtained by combining the various components of uncertainty that characterize the measurement. In other words, the measured quantities should represent the measurand.

In order to estimate the flow measurement $\dot{q}$ in a pipe prover, main dimensions represented by: linear length l, tube sectional area a and travelling time t are related as shown in Eq. 1.

$$\dot{q} = \frac{[l][a]}{[t]} \tag{1}$$

In order to consider statistic variations, each variable in Eq. 1 has to be added to the respective standard uncertainty. Thus Eq. 1 can be rewritten as seen in Eq. 2:

$$\dot{q} = \frac{[\bar{l} + u(\bar{l})][\bar{a} + u(\bar{a})]}{[\bar{t} + u(\bar{t})]} \tag{2}$$

Where $u(x_i)$ represents the uncertainty associated to each variable x_i, considering l, a and t as x_1, x_2 and x_3, respectively.

Uncertainties evaluations are based on frequency distributions for a random variable, for which n independent observations are obtained under same conditions of measurement process. For example, consider a random variable x_i where $x_{i,k}$ independent observations are taken, thus a good averaged estimative of x_i is represented by $\bar{x}_i$ as demonstrated in Eq. 3.

$$\bar{x}_i = \frac{1}{n} \sum_{k=1}^{n} x_{i,k} \tag{3}$$

Then for each measurement represented by l, a and t, the measurand may be given by: $X_i = \bar{x}_i + \Delta x_i$, or X_1, X_2 *and* X_3 respectively. A good estimative of X_i is represented by $\bar{x}_i$ with variations $x_{i,k}$ that, due to random effects, its experimental variance has to be defined as indicated by Eq.4:

$$s^2(x_{i,k}) = \frac{1}{n \quad 1} \sum_{k=1}^{n} (x_{i,k} - \bar{x}_i)^2 \tag{4}$$

The component of the uncertainty that represent the variations $x_{i,k}$, in average, will be the square root of the experimental variance divided by n observation as is represented by the Eq.5 (GUM.2003):

$$u^2(\bar{x}_i) = s^2(\bar{x}_i) = \frac{s^2(x_{i,k})}{n} \tag{5}$$

For the determination of the uncertainty of each variable that defines the flow of liquid, it is necessary to combine each result according to the mathematical relationship between them. The basic rules for the propagation of uncertainty suggested by Ribeiro (2010), which simplifies the calculations and does not require the use of partial derivatives and coefficients of sensitivities, are:

- In addition and subtraction operations, uncertainties are propagated by the sum of absolute uncertainty (or standard uncertainty).
- In multiplication and division operations, uncertainties are propagated by the sum of the related uncertainties.

In addition, for the propagation estimative of dependent uncertainties, the sum of the uncertainties is straightforward. For the propagation of independent uncertainty the sum of the uncertainties is made by the square root of the sum of squares of the related uncertainty as defined below:

Propagation of uncertainty in operations of addition and subtraction is given as in Eq.6.

$$u_c = \sqrt{u(x_1)^2 + \ldots + u(x_i)^2} \tag{6}$$

Propagation of uncertainty in operations of multiplication and division is given Eq.7.

$$\frac{u_c}{\bar{x}_1 + \ldots + \bar{x}_i} = \sqrt{\left(\frac{u(x_1)}{\bar{x}_1}\right)^2 + \ldots + \left(\frac{u(x_i)}{\bar{x}_i}\right)^2} \tag{7}$$

Although the combined standard uncertainty can be universally 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 coverage factor, as represented by Eq.8.

$$U = k * u_c(\dot{q}) \tag{8}$$

The choice of factor *k* depends on the coverage probability or occurrence of the required range. Assuming a normal distribution and a desired confidence, coverage factors values are defined as listed in Tab. 1.

Table 1 - Coverage Factor (normal distribution)

Confidence level p (percent)	Coverage Factor k_p
68,27	1,00
90,00	1,64
95,00	1,96
95,45	2,00
99,00	2,58
99,73	3,00

4. VOLUME CALCUTATION METHODOLOGY

The statistical calculation of the pipe prover volume is done through direct measurements of pipe dimensional length between sensors and diameter of pipe. Similarly the sphere's translation time between sensors is registered by an electronic board when the sphere passes in front of each sensor.

The estimated flow in pipe prover is achieved by a combination of measured length, pipe cross-section area and travel time registered, as indicated by Eq 1, each of them is done independently considering similar initial conditions. Details of the methodology for measurements made can be found in Lavezzo (2010).

Measurements for the pipe length are obtained from readings observed in straight stretchs, with the use of a laser tape measure, as shown in Tab. 2.

The pipe section code is demonstrated in Fig. 4 and Tab. 3 and its depends on flow direction: clockwise and counterclockwise. Each section is defined by infrared sensors at start and ending position and section 2-3 is composed by the sum of sections 2-2', 3-3' over the stretch in a curve provided by the manufacturer with 0,513m and adopted with zero uncertainty.

The estimate of $\bar{l}$ for each section is given by Eq.3 and the determination of uncertainty for the measurements raised is given by Eq. 5. The propagation of uncertainty for the full stretch and the stretch curve will be the sum of the absolute uncertainties given by Eq. 6.

Table 2 – Independent readings of the straight stretchs

	Independent readings (m)									
Section tube code	1	2	3	4	5	6	7	8	9	10
1-2	2,997	2,997	2,997	2,998	2,997	2,997	2,996	2,997	2,996	2,997
2-2’	1,240	1,241	1,241	1,240	1,241	1,241	1,240	1,240	1,240	1,240
3-3’	1,245	1,246	1,245	1,245	1,246	1,245	1,245	1,246	1,245	1,246
3-4	2,998	2,997	2,998	2,998	2,997	2,998	2,997	2,998	2,997	2,998

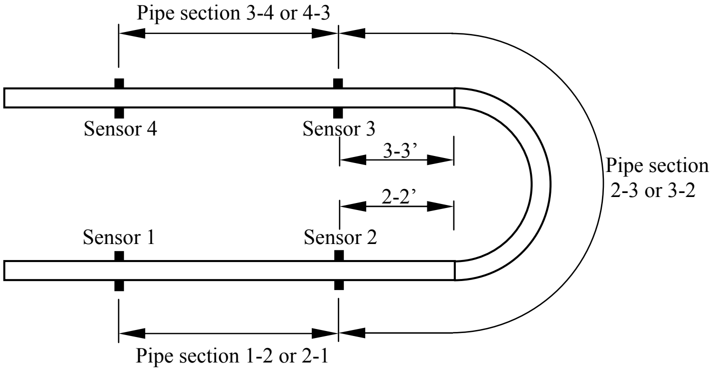


Figure 4 – Pipe sections code

Table 3 – Section pipe code

Section tube code	Start Sensor	End Sensor	Direction
1-2	1	2	counterclockwise
2-3	2	3	counterclockwise
3-4	3	4	counterclockwise
4-3	4	3	clockwise
3-2	3	2	clockwise
2-1	2	1	clockwise

Similarly the determination the area of the pipe and the associated uncertainty is obtained through of the readings from the pipe diameters of the cross-section of the pipe using a caliper, as shown in Tab.4.

Table 4 – Independent readings of tube cross-section

	Independent readings									
	1	2	3	4	5	6	7	8	9	10
Diameter ϕ (mm)	53,05	53,00	53,00	53,00	53,00	53,00	52,95	53,05	53,05	53,05
Cross-Section (m²)	0,00221	0,00220	0,00220	0,00220	0,00220	0,00220	0,00220	0,00221	0,00221	0,00221

Likewise in calculation of the lengths, the estimation for $\overline{a}$ is given by Eq. 3 and its uncertainty by Eq. 5. In this case the combined uncertainty is given by Eq 7, since area is the result of a product diameter.

The volume in the pipe prover between the sensors 1-2, 2-3, 3-4 and the total volume in pipe prover between the sensors 1 until sensor 4 can be view by Tab.5.

In possession of the estimate volumes on each section, the flow $\dot{q}$ described by Eq.3 will be the combination of volume measurings multiplied by the sphere estimated traveling time $\bar{t}$. In this case, the uncertainty will spread from Eq. 7.

Table 5 – Base volume by stretch

Pipe section	Base volume (l)	Measured volume (l)	Absolute uncertainty (l)	Relative uncertainty (%)
1-4	Vb_{1-4}	19,85	0,02	0,000901
1-2	Vb_{1-2}	6,62	0,01	0,000902
2-3	Vb_{2-3}	6,62	0,01	0,000904
3-4	Vb_{3-4}	6,62	0,01	0,000902

Sphere travel time readings are recorded simultaneously to turbine meter pulses. The comparison between the two records is done through an interpolation process. Such procedure is necessary to consider the fractional part of a pulse that can contribute to the error in measuring when the pipe prover is compared with turbine meters. The combination of the interpolation pulses emitted by turbine meters and the travel time of the pipe prover can be viewed by Fig.5.

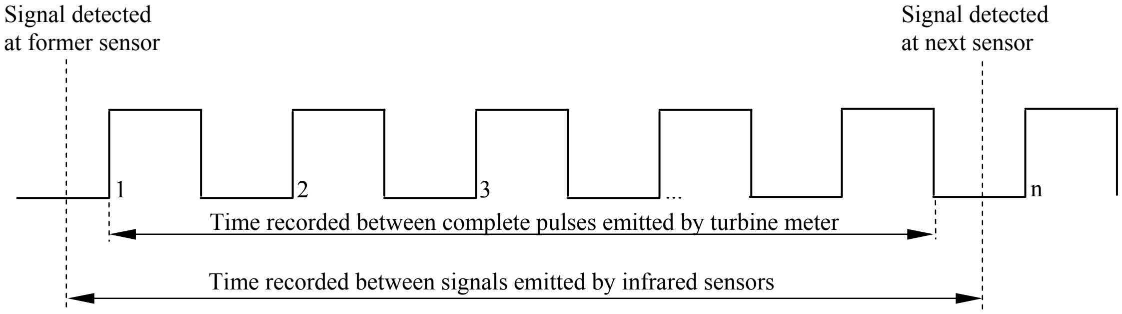


Figure 5 – Interpolation pulses scheme

5. RESULTS AND DISCUSSION

Pipe prover was tested under three distinct flow levels, keeping similar temperature and pressure conditions. For a matter of synthesis, just maximum flow is presented here.

Experimental data is treated as described in section 3 and listed as Tab. 6, where second column indicate the mensurand (flow rate) considering acquired time data averaged from 20 consecutive cycles runs and considering each section tube and direction (clockwise or counterclockwise) indicated by first column.

Flow uncertainty is shown at third column. Fourth and fifth columns show turbine k-factors propositions, as a calibration process. Sixth column presents the relative difference between clockwise and counterclockwise measuring, considering each pipe section.

Mensurand listed in Tab. 6 is plotted in Fig. 6, presenting a strong trend to stability, around 0,329 l/s ±0,0045%, which indicates a good quality measurement.

Table 6 – Experimental data summary at maximum flow rate

Pipe section	Mensurand (l/s)	Uncertainty U (%)	Correction factor		Relation : (clockwise-counterclockwise)
			Factor-k (Double-Timing)	Meter Factor	
1-2	0,329	0,00	500,13	1,000806	-0,109%
2-1	0,329	0,00	498,18	1,004639	
Average / U_c	0,329	0,0048	499,15	1,002722	
2-3	0,330	0,00	498,37	1,004261	-0,004%
3-2	0,330	0,00	496,95	1,007118	
Average / U_c	0,330	0,0049	497,66	1,005689	
3-4	0,330	0,00	496,92	1,007205	0,191%
4-3	0,330	0,00	496,21	1,008637	
Average / U_c	0,330	0,0053	496,56	1,007921	
1-4	0,329	0,00	498,46	1,004105	-0,004%
4-1	0,329	0,00	497,11	1,006793	
Average / U_c	0,329	0,0045	497,79	1,005449	

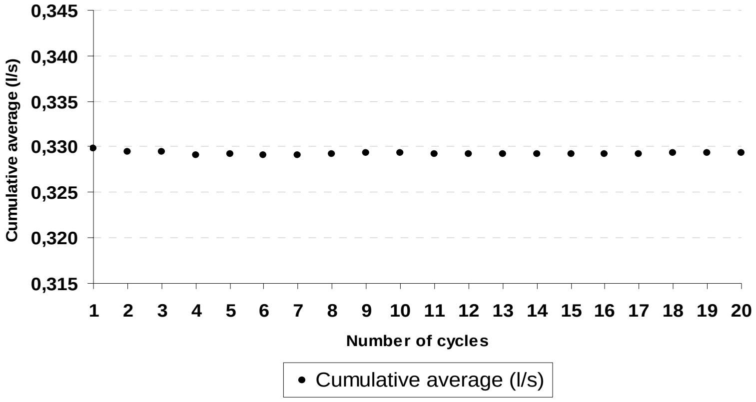


Figure 6 – Accumulated averaged volume at maximum flow rate, considering 20 cycles (clockwise and counterclockwise directions)

Pipe prover was submitted to relative three levels of low flows presenting the behavior demonstrated in Tab. 7. Respective Reynolds numbers were listed as well.

Table 7 – Summary of pipe prove operational flow measurements

Averaged flow rate (l/s)	Uncertainty (%)	Reynolds number
0,137	0,036	$4,0 \times 10^3$
0,228	0,0072	$6,8 \times 10^3$
0,329	0,0045	$9,9 \times 10^3$

In Fig. 7 are plotted flow readings considering each direction and section pipe, at three consecutive measurement runs. As can be visualized, there is a smooth trend to sphere acceleration in the clockwise direction, since flow readings are increasing in sections 1-2, 2-3 and 3-4, although slowdown movement is perceived in the opposite direction (sections 4-3, 3-2 and 2-1). The acceleration motion is not observed in averaged measurements considering complete cycle in both directions.

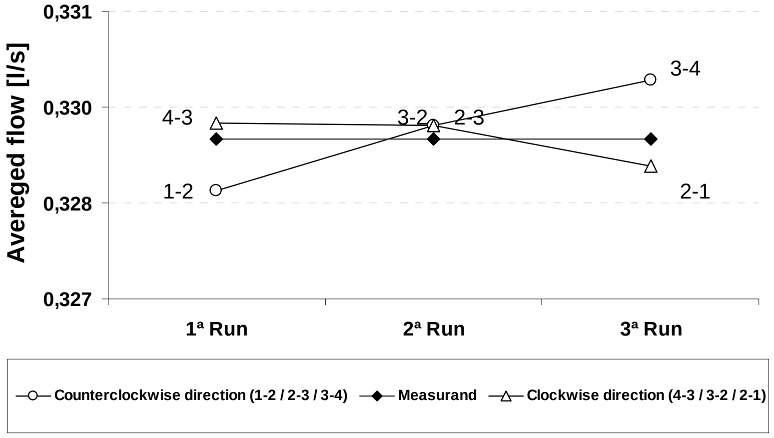


Figure 7 – Flow rate behavior considering section pipe and direction (clockwise and counterclockwise) for three consecutive cycles

Such behavior has been interpreted as a consequence of a slightly smaller diameter somewhere at section tube 1-2. This reflection is turned possible just through the presence of four sensors pairs arrangement, instead of usual two pairs system, typical of industrial applications. Averaged flow rates present a good stability in Fig. 7 as already observed in Fig.6.

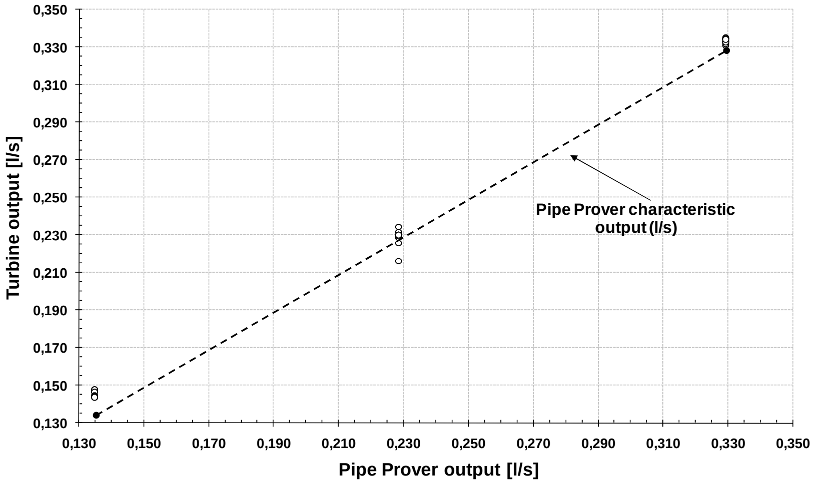


Figure 8 – Turbine vs. pipe prover correlation at three distinct flow rates

Flow rates readings from turbine and pipe prover are correlated and plotted in Fig. 8 considering three distinct flow levels. In this comparison it is considered the turbine k-factor as calibrated by manufacturer (k=500,3), which is +0,5% than presented at Tab.6, for tested flow rates .

It can be seen that, besides presenting a correlation closed to linear, the agreement between readings is much better at maximum flow rate than at lower rates. Such comparison could not be considered reasonable since such condition is out of turbine operational manufacturer specifications (0,19-1,89 l/s). On the other hand, pipe prover reading keeps its stability at such condition.

Although behavior of laboratorial pipe prover has been determined, it is desirable to extent such analysis considering variation of operational parameters, as pressure and temperature. The use of infrared sensors demonstrated to be a good practice to deal with clear work fluids, since it is not intrusive, but it is necessary some development of sensors systems to operate with dark fluids as well. Most of initial questions formulated at section 1 were satisfactorily answered.

6. ACKNOWLEDGEMENTS

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