METROLOGICAL EVALUATION OF THE INTERLABORATORIAL COMPARISON OF THE ULTRASONIC FLOWMETER CALIBRATION

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Abstract. *This work deals with the metrological evaluation of the same ultra-sonic flowmeter, when calibrated in two different calibrating systems, belonging, respectively, to two accredited laboratories, both operating according to the manufacturer's installation technical specification, and following the minimum requirements, as specified in international standards and recommendations. The research investigated the effect in calibration of the installation of a valve and a long curve upstream of the measurement straight section, as dimensioned according to the applicable standards. It was concluded that longer straight sections should be specified, so that the influence of the installation in the calibration could be neglected. The development of the present work was motivated by the growing utilization of ultrasonic flowmeters by the oil industry, and by the urgent need to contribute to the advance of the technology and the applicable standardization. In this aspect, this work contributes to (a) a better understanding of the measurement technology and of the calibration procedure of ultra-sonic liquid flowmeters, (b) the advance of the technology standardization, since it includes a critical analysis of the minimum requirements, as specified by the standards, and (c) improving the laboratory accreditation criteria for flow meter calibration, because the influence of the installation in the calibration was experimentally shown.*

Keywords*: Metrology; Ultrasonic flowmeter measurement; transit time; measurement system; calibration system; petroleum.*

1. INTRODUCTION

The OIML R117 (1995) international recommendation requires that the maximum permissible errors for accuracy class 0.3 complete liquid measuring systems be 0,3 % of the measured volume for all pressure, temperature and flowrate values for which they are designed for, or have been approved, without any adjustment between various tests for pattern approval, initial verification and subsequent verifications. A 0,2 % value is allowed for the meter itself. In Brazil, a government decree (ANP / INMETRO N°1 Joint Decree, 2000) established the conditions and the minimum requirements an oil and a natural gas measuring system has to meet, in order to assure accurate and complete results. Another government decree (INMETRO N° 064, 2003) approved an oil measuring technical regulation, establishing the technical and metrological requirements an oil production fiscal measurement system must meet in order to be used for custody transfer, allocation and operational purposes. The fiscal metering points must be submitted to the analysis of the metrological control of INMETRO (National Institute of Metrology and Industrial Quality) , if adequate, in order to demonstrate their traceability to measurement standards, and then be approved by ANP (National Agency for Petroleum, Natural Gas and Biofuels).

Positive displacement, turbine or mass (Coriolis) types of online fluid measurement systems can be used in the fiscal metering points. Other types of systems must be submitted to the analysis and approval by ANP. Online fiscal metering systems of the petroleum production must be calibrated every sixty (60) days at most. Larger calibration intervals may be approved by ANP on the basis of historical records. The calibration of online fiscal metering systems must be made with the same measurement fluid and flow conditions, within a maximum allowed deviation of 2 % in specific mass and viscosity, 5 °C in temperature, 10 % in pressure, and 10 % in flow rate. Provers, tanks, measurement standards or other previously authorized system by ANP can be use in the calibration as the reference meter.

The transit time ultrasonic flowmeter has been studied for measuring flow rate, and thus volume, for having the potential of being very accurate, meeting the metrological requirements for fiscal measurement with no pressure drop and, at the same time, providing a basis of performance diagnostic between two consecutive calibrations.

Ultrasonic flow meters (UFM) measure the average axial flow velocity along an acoustic path in a pipeline, which can be related to the volumetric flowrate, if the flow velocity profile is known. Completely developed turbulent flows have been well studied, and are easy to be reproduced, provide that a long straight pipeline exists upstream and downstream of the meter. This relationship is a function of Reynolds number, as indicated by the available literature (Schlichting, 1968). Or, it can be obtained by calibration in a laboratory. However, this is seldom the case, because there is a lack of space in most measuring installations. Upstream fittings, valves, reducers and elbows can produce velocity profile distortions at the meter inlet that may result in flow rate measurement errors. The amount of meter error will be dependent on the type and severity of the flow distortion produced by the upstream piping configuration and the meter's ability to compensate for this distortion. Research has demonstrated that asymmetric velocity profiles may persist for 50 pipe diameters or more downstream of the point of initiation. Swirling velocity profiles may persist for 200 pipe diameters or more. In order to achieved the desired meter performance (AGA Report No. 9, 2007), it may be necessary to alter the original piping configuration or include a flow conditioner as part of the metering package to eliminate the effects of the upstream flow disturbance. For custody transfer applications, the use of flow conditioning is recommended to minimize flow distortion. The use of several acoustic paths in UFM can contribute to compensate for the distortion.

The AGA Report No. 9 (2007) describes a series of flow verification tests, with a set of flow disturbance elements placed upstream of the meter, to verify the meter performance for gas measurement, which can be applied to liquid measurement, according to the fluid mechanics theory. The specified upstream piping installations are intended to create a representative range of flow distortions that are typical of what may be produced in field service at the inlet to the meter run. Firstly, the meter is calibrated in a baseline configuration that consists of a fully developed, symmetric, swirl-free turbulent velocity profile at the inlet of the meter, or test assembly, that includes a flow conditioner. Then, the system is submitted to the following flow disturbances upstream of the meter, with the performances compared :

- Disturbance 1 : Two closely-coupled, 90° long-radius elbows in perpendicular planes to access the effects of a modest degree of swirl and a non symmetrical velocity profile.
- Disturbance 2 : A single elbow to access the effect of strong secondary flow with flow asymmetry and no swirl.
- Disturbance 3 : A gate valve 50 % closed to access the effect of a strong non-symmetrical velocity profile.
- Disturbance 4 : A swirl generator to access the effect of a high degree of swirl.

In this paper, as a first step to the complete flow verification set of tests, a KROHNE ALTOSONIC V UFM was tested in two accredited calibration laboratories in Brazil for the purpose of checking the meter performance in different existing piping and flow circulation configurations of the test facilities (Two 90° elbows in the same plane). Water and oil were used as calibrating fluids for a wide flow rate range.

2. THE ULTRASONIC FLOW METER

2.1 Principles of ultrasonic measurement

The ISO/TR 12765 (1998) and the API MPMS 5.8 (2005) standards presents the fundamentals of fluid flow rate measurement in tubes with ultrasonic meters using the transit time method. Fig. 1 shows the ultrasonic beam making an angle ϕ with the flow direction in the tube, with internal diameter ***D***. The beam emitter ***1*** and the beam receiver ***2*** are placed on the surface of a tube, and are separated by a distance $\mathbf{L_p}$ along the direction of the flow **.**

A five (5) beam ultrasonic meter (KROHNE ALTOSONIC V) was installed in Marlim Asset for fiscal flow measurement purposes. Two of them are placed symmetrically in the middle distance, approximately, between the center line and the wall, measuring the average velocities along the beam paths $\overline{u}_2$ and $\overline{u}_4$. Two of them are placed symmetrically near the wall, measuring the average velocities along the beam paths $\overline{u}_1$ and $\overline{u}_5$. Finally, the last one is placed along the center line, measuring the average velocity along the beam path $\overline{u}_3$. The average flow velocity ($\overline{u}$) is related to transit times t_{12} and t_{21} by Eq. (1).

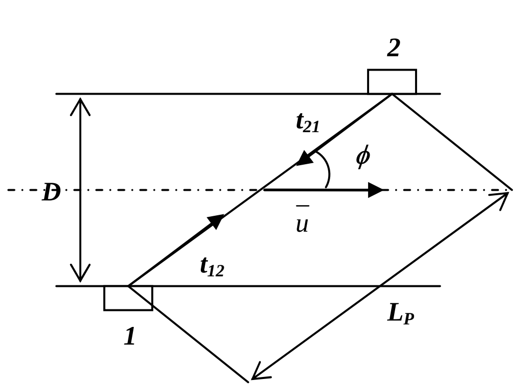

Figure 1 : Schematics of ultrasonic meter using the transit time method

$$\frac{1}{t_{21}} - \frac{1}{t_{12}} = \frac{2.\bar{u}.\cos(\phi)}{L_p} \quad (1)$$

Orlando & Do Val (2006a) showed that the average velocity along the beam path, as measured by the meter, and the fluid velocity at a point of the cross section equally distant from the center line than the beam path, are approximately the same. Therefore, the flow profile can be defined by five (5) points. The average flow velocity at the cross section ($\bar{u}$) can be estimated by means of the Gauss method, using Legendre polynomials, as shown by Eq. (2). A fine tuning can be done by calibrating the meter as a function of Reynolds number, resulting in the volumetric flow rate at the operating conditions.

$$\bar{u} = \frac{1}{2}\sum_{i=1}^{5} w_i.\bar{u}_i = 0{,}236926.\frac{(\bar{u}_1 + \bar{u}_5)}{2} + 0{,}478828.\frac{(\bar{u}_2 + \bar{u}_4)}{2} + 0{,}568888.\frac{\bar{u}_3}{2} \quad (2)$$

Before delivering the instrument to the client, the manufacturer calibrates the meter as a function of the Reynolds number (Re), thus characterizing its performance in an operation called *fingerprint.* During this operation, flow rate and viscosity are varied in such a way that all the Reynolds number range can be covered. In fact there is no need of calibrating the meter at the same measuring flow rate and viscosity, provided the Reynolds numbers during calibration and operation are the same.

The calibration provides a correction factor to the value calculated in Eq. (2), as a function of Reynolds number, so that the average flow velocity, and thus the flow rate, can be estimated from the measured velocities along all five acoustic paths.

The purpose of the performance verification is to determine if the difference between the initial values and the measured values of the flow rate is still smaller than what is specified by OIML R117 (1995).

Orlando & Do Val (2006b) analyzed the calibration certificates of the meter and showed that its performance meets the OIML R117 requirements for a large range of Reynolds number.

2.2 Calibration and verification of the ultrasonic meter

The initial calibration of the meter, made by the manufacturer, is called *fingerprint.* The *Meter Factor,* defined as the ratio between the indicated values by the measurement standard and the meter during calibration, is calculated for a large number of Reynolds number values, so that during measurement an interpolation procedure can result in reliable values of the flow rate, according to OIML R117 Accuracy Class 0.3.

The acceptance of the meter for fiscal metering purpose is done through the so-called performance verification procedure of the meter, where at least six (6) nominal flow rate values are chosen along the whole range. The *Meter Factor* for each flow rate value is calculated at least three (3) times, so that the repeatability, defined as the difference between the larger and smaller values, can be estimated and expressed percentage wise.

The INMETRO No. 064 Decree (2003) and OIML R117 recommendation (1995), specify that the meter can be approved if, during the verification tests, all *Meter Factor* (MF) errors are less than ± 0,2 %. Moreover, the MF repeatability , for each flow rate, must be at most 0,12 %.

2.3 Metrological characterization of the ultrasonic flow meter.

Da Mata et Allii (2008) analyzed several calibration certificates for the 150 mm, 300 mm and 600 mm diameter KROHNE ALTOSONIC V ultrasonic meters, aiming their approval for Accuracy Class 0.3. They were issued by three accredited laboratories in Europe : SPSE and TRAPIL in France, NMI in Holland. The following calibration fluids, with viscosity measured at 20 °C, were used : Fuel (186 cSt), Heavy Fuel (271 cSt), Condensat (37-77 cSt), Oural (9,3 cSt) and water (1 cSt).

In this study, the metrological quality of the meter is characterized by how close the *Meter Factor* (MF) is to 1, and its dispersion, defined as twice the standard deviation (2.σ) of the *Meter Factor* (MF) in each analyzed condition. Tab. 1, 2, 3, 4 and 5 show the results from Da Mata et Allii (2008).

As it can be seen the ultrasonic meter is very repeatable and its performance is quite independent from diameter, viscosity and flow rate.

Table 1 - Metrological quality as a function of meter diameter.

DIAMETER	METER FACTOR	DISPERSION
mm		(2.σ)
150	1,0000	0,0016
300	1,0000	0,0015
600	1,0001	0,0016
AVERAGE	1,0000	0,0016

Table 2 - Metrological quality as a function of calibration fluid and viscosity, 600 mm diameter meter.

FLUID	METER FACTOR	DISPERSION
		(2.σ)
HEAVY FUEL	1,0002	0,0018
FUEL	1,0000	0,0014
CONDENSAT	1,0001	0,0015
OURAL	1,0001	0,0018
WATER	0,9999	0,0016
AVERAGE	1,0001	0,0016

Table 3 - Metrological quality as a function of Reynolds number, 600 mm diameter meter.

REYNOLDS	METER FACTOR	DISPERSION
		(2.σ)
200 a 2000	1,0002	0,0018
2000 a 10000	1,0001	0,0015
10000 a 30000	1,0002	0,0014
30000 a 100000	0,9998	0,0016
100000 a 1000000	1,0005	0,0006
1000000 a 3500000	0,9995	0,0012
AVERAGE	1,0001	0,0016

Table 4 - Metrological quality as a function of flow rate, 600 mm diameter meter.

FLOW RATE	METER FACTOR	DISPERSION
(m^3/h)		(2.σ)
200 a 500	1,0001	0,0016
500 a 1000	1,0002	0,0018
1000 a 1500	1,0001	0,0019
1500 a 2000	1,0000	0,0011
2000 a 2500	1,0002	0,0017
2500 a 3000	1,0001	0,0012
3000 a 6000	0,9998	0,0017
AVERAGE	1,0001	0,0016

Tabela 5 - Manufacturing and calibration repeatability of the 600 mm diameter meter

METER	METER FACTOR	DISPERSION
		(2.σ)
232575-1001	1,0002	0,0017
232575-3001	1,0000	0,0014
232575-3002	0,9999	0,0018
232575-5001	1,0002	0,0015
232575-7001	1,0002	0,0015
232575-9001	1,0000	0,0019
232575-9002	1,0000	0,0014
AVERAGE	1,0001	0,0016

3. THE CALIBRATING FACILITIES

3.1 Measuring section

In order to test the performance of the UFM in different facilities, tests were made in two accredited laboratories by the Brazilian Calibration Network. In LAB A the flow is circulated in a closed loop until a stable flow is established. Then a diverter directs the fluid to a prover, where it is weighted. In LAB B, a pump is turned on and immediately directs the fluid to a prover, where the volume is measured, as described by (API MPMS 4.8, 1995). In both systems the prover is an open tank. The basic schematic of the common part of the testing facility for both laboratories is shown in Fig. 2.

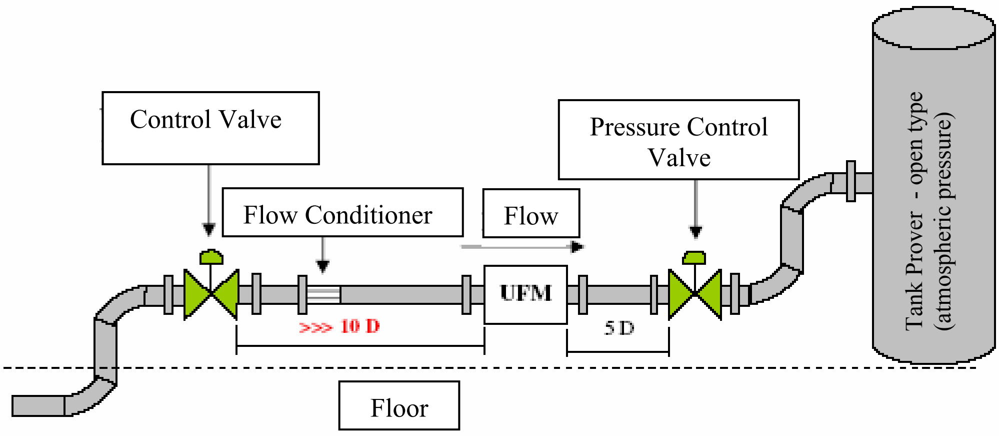

Figure 2 : Basic schematic of the testing facilities.

In order to assure an accurate measurement, API MPMS 5.8 (2005) recommends that the straight pipeline length between the meter and the flow conditioner must be at least 10 D. The distance between the control valve and the flow conditioner must be at least 10 D. The straight pipeline length downstream of the meter must be at least 5 D.

The tank prover is a calibrated vessel used to measure the volume of the liquid inside it. The ratio between the prover volume and the indicated meter volume is called the Meter Factor (MF). In this measuring system, some precautions must be taken in order to prevent the effects of starting and stopping the flow into the prover from influencing the measurement. Alternately, the liquid inside the prover can be weighted, rather than having its volume measured. According to API MPMS 4.8 (1995), the MF repeatability between five (5) consecutive runs, defined as the difference between the maximum and minimum measured values, must be to within 0,05 %.

When a master meter is used for calibration, the repeatability must be to within 0,02 %.

3.2 Tests in LAB A

Tests were conducted in LAB A with water as a working fluid to check the influence on the volume measurement of the several parameters, simulating at the same time the calibrating conditions of LAB B. A 4” meter was used. Two types of flow regime were tested. (a) Steady state : Using the diverter to direct the fluid to the tank prover (less than ± 0,12 % uncertainty) when the flow is stable, (b) Transient : Directing the fluid to the tank prover when the run starts by opening a valve, without using the diverter.

Tab. 1 shows the combinations of the different parameters used in five (5) tests. Tab. 2 shows the relative errors of each run (with respect to LAB A standard measurement indication). Tab. 3 shows the repeatability of results.

Table 1 : Testing conditions for LAB A.

PARAMETERS	TESTING CONDITIONS				
	C1T1	C2T1	C2T2	C2T3	C2T4
Flow Regime	Steady State	Steady State	Transient	Transient	Transient
Straight pipeline length	40 D	10 D	10 D	10 D	10 D
Proven fluid volume	15 m^3	15 m^3	5 m^3	5 m^3	5 m^3
Flow rates (m^3/h)	167,80,30	80,60,40,30	80,60,30	80,60,40,30	80,60,40,30
Number of runs	3, 3, 3	3, 3, 3, 3	3, 3, 5	3, 3, 3, 3	3, 3, 3, 3

Table 2 : Relative errors of each run (with respect to LAB A standard measurement indication)

FLOW RATE	RELATIVE ERRORS (%)				
m³/h	C1T1	C2T1	C2T2	C2T3	C2T4
30	-0,05	0,04	0,06	0,07	0,06
30	-0,07	0,04	0,06	0,11	0,04
30	-0,06	0,06	0,05	0,04	0,05
40		0,06		0,08	0,04
40		0,05		0,09	0,08
40		0,04		0,06	0,07
60		0,07	0,03	0,15	0,10
60		0,04	0,03	0,05	0,08
60		0,12	0,05	0,08	0,07
80	-0,04	0,11	0,06	0,18	0,19
80	-0,05	0,13	0,05	0,17	0,12
80	-0,01	0,16	0,16	0,13	0,15
80			0,16		
80			0,12		
167	0,04				
167	0,01				
167	0,03				

Table 3 : Repeatability of results for LAB A.

FLOW RATE	RELATIVE ERRORS (%)				
m³/h	C1T1	C2T1	C2T2	C2T3	C2T4
30	0,01	0,02	0,02	0,07	0,02
40		0,02		0,03	0,04
60		0,09	0,02	0,10	0,03
80	0,04	0,05	0,11	0,05	0,07
167	0,03				

Analysis of Tab. 2 and 3 shows that both relative errors and repeatability meet the OIML R117 (1995) tolerances, respectively, ± 0,20 % and 0,12 %, independently of flow regime, straight pipeline length upstream of meter, proven fluid volume and flow rate. However, only C1T1 run meets the manufacturer's repeatability tolerance (0,04 %). Comparing C1T1 run (40 D) to C2T1 (10 D) run results, it can be concluded that a larger straight pipeline length upstream of the meter is important for meeting the manufacturer's repeatability tolerances.

3.3 Testes in LAB B.

Two sets of tests were made in LAB B. The first one, using water as a working fluid and a tank prover for volume measurement (less than ± 0,12 % uncertainty), to be compared to LAB A results. The second one, using a mineral oil as a working fluid and a lobed impeller flow meter for volume measurement (± 0,15 % uncertainty). A transient type flow regime was used, that is, the fluid was directed to the tank prover or master meter, when the run was started. Tab. 4 shows the testing conditions.

Table 4 : Testing conditions for LAB B.

PARAMETERS	TESTING CONDITIONS	
	TEST 1	TEST 2
Flow regime	Transient	Transient
Meter size	4"	8"
Working fluid	Water	Mineral Oil
Measurement Standard	Tank prover	Master meter
Proven fluid volume	5 m³	6 m³
Flow rate m³/h	150,120,83,30	500,400,300

Table 5 : Relative errors and repeatability of each run (with respect to LAB BA standard measurement indication)

Flow rate	Relative errors (%)						Repeatability
m³/h	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	%
30	-0,56	-0,59	-0,65	-0,66	-0,69		0,13
83	-0,42	-0,51	-0,42	-0,39	-0,48	-0,48	0,12
120	-0,44	-0,42	-0,41	-0,45	-0,45		0,03
150	-0,42	-0,45	-0,41	-0,38	-0,40	-0,41	0,07

Analysis of Tab. 5 shows that relative errors do not meet the OIML R117 (1995) tolerances (± 0,20 %); repeatability meets tolerance (0,12 %) only for higher flow rates; manufacturer's tolerance (0,04 %) is not met for most flow rates. Due to different results between LAB A and LAB B, it was decided to compare the outputs from the UFM (ultrasonic flow meter) and a Master Meter (lobed impeller flow meter). A S-600 Emerson Process Flow computer was used to measure the flow rate every 0,5 s, using a *Intoch* software and the results are shown in Fig. 3. The volume is calculated by integrating the flow rate along the time interval. This is done by counting the number of output pulses from the meters, which are automatically available.

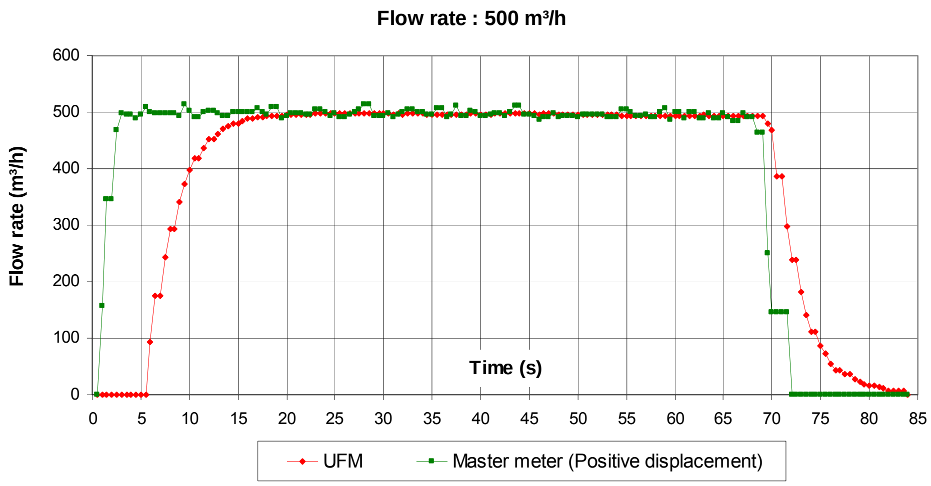

Figure 3 : UFM and Master Meter Outputs during a complete run (500 m³/h).

Table 6 : UFM volume measurement error for complete run and effective run.

RUN	VOLUME MEASUREMENT ERROR (%)					
	300 m³/h		400 m³/h		500 m³/h	
	Complete	Effective	Complete	Effective	Complete	Effective
1	-2,63	0,20	-4,94	-0,27	-5,45	1,83
2	-2,52	-0,08	-4,73	0,17	-5,70	0,63
3	-10,19	-0,12	-5,14	0,41	-5,87	1,11
4	-9,52	0,25	-4,74	0,53	-6,69	0,45
5	-9,36	0,63	-5,31	-0,44	-5,61	-0,92
6	-8,75	-0,22	-5,36	0,66		
7	-9,33	0,83				
9	-8,95	1,73				
11	-8,95	-0,52				
12	-8,96	1,17				
13	-9,42	0,88				
14	-8,84	-1,70				
15	-8,15	1,30				
16	-8,55	-1,02				

The master meter is a positive displacement meter and the influence of opening and closing the control valve for, respectively, starting and stopping the run, is small. However, due to the flow transient, the velocity profile is only stable after some time and the delay causes an error in flow measurement by the UFM, if the total time interval is used for comparison (complete run). In order to minimize this effect, an effective time interval must be selected (effective run) in which the transients effects can be neglected and the flow rates indicated by the meters, and thus the volumes, can be compared for calibration purposes. Tab. 6 shows the UFM volume measurement error for two situations. (a) Complete run, (b) Effective run.

4. CONCLUSIONS

The experiments showed that the ultrasonic meter performance, as defined by its maximum allowable error and repeatability of measurement, is dependent on the type of pipeline disturbances upstream and downstream of the meter. It was concluded that a straight pipeline length of 40 D upstream of the meter can considerably reduce the errors and repeatability of the meter, which is much larger than what is recommended by API MPMS 5.8 (2005).

No conclusion could be obtained about the influence on the meter performance of the calibration procedure and the proven fluid volume used in the experiments, as indicated by OIML R 117 (1995).

The experimental data confirmed the need of having a stable flow regime for measuring the flow with the ultrasonic meter. Transient flows result in measurement errors by the ultrasonic meter and are to be avoided..If this is not possible, the calibration can be done only after sometime, so that the flow becomes stable.

Based on the experimental data it is recommended that at least a 40 D straight pipeline length be used in calibration for minimizing meter measurements errors and repeatability. This value is much larger than what is recommended by the standards and is adopted by two laboratories in this study.

5. ACKNOWLEDGEMENTS

The authors are indebted to PETROBRAS for having provided the ultrasonic meter and the means for its calibration in the accredited laboratories

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5. RESPONSIBILITY NOTICE