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Pitometry as a validation tool for water flow measurement in large diameter pipelines

Nilson Massami Taira[1], Kazuto Kawakita[1], Valmir Ruiz[1]

[1] *IPT-Instituto de Pesquisas Tecnológicas*
Av. Prof. Almeida Prado 532 CEP 05508-901 São Paulo/SP Brazil
nmtaira@ipt.br, kawakita@ipt.br, valmir@ipt.br

Abstract

Accurate measurement of water flow rates in large diameter pipelines is a challenge for water companies that need to produce, transport and distribute increasing quantities of water. To a large extent, this challenge results from the impossibility of recalibration of the flow meters within the periodicity established in the metrological regulations since the removal of a large flow meter from its site of operation in the field and its dispatch to a calibration laboratory is in most cases technically and economically impracticable. As a result of this scenario, the article presents the pitometry technique as an interesting alternative to solve problems related to the validation of water flow measurements performed by flow measurement systems installed in large pipelines. The technique is based on the determination of the water flow rate by mapping the velocity profile of the water flow inside the pipe using Cole type Pitot tubes. The water flow rate is determined in a cross section of the pipe located near and in series to the flowmeter to be evaluated. Based on the results obtained in a great number of water flow measurements already performed by applying the pitometry technique in large diameter pipelines in the field, it is possible to conclude that this methodology is perfectly applicable in the validation of the performance of flow meters installed in these conduits solving satisfactorily the issues related to its operation.

1. Introduction

Due to technical and economic reasons, the accurate measurement of water flow rates in large diameter pipelines is a challenge for water supply companies that everyday need to produce, transport and distribute increasing quantities of this product. It is also an incitement for manufacturers of flowmeters that are requested to offer solutions to this progressively challenging metrological demand.

In the last decades, based on the development of sensors, electronic signal processors and software, it has been possible to witness the emergence of new water flow measurement technologies for these applications such as the widely used electromagnetic full bore meters, the ultrasonic transit time flowmeters and the electromagnetic and thermal insertion meters that are proposed to replace the former differential pressure meters such as the well-known Venturi tube and its several constructive variations. These developments have been induced by the need for automation and control of water flow measurement processes associated with the requirement for improving the reliability of flow measurement results.

Despite the natural process of modernization of the flow measurement systems used by the water companies, what has happened in practice is a series of issues arising from the application of these new technologies in such situations. Notably, the following topics deserve mention:

- the issue of recalibration of the flowmeters within the periodicity established in metrological regulations still remains unresolved. The removal of a large full-bore diameter flowmeter from its site of operation in the field and its dispatch to a calibration laboratory is in most cases technically and economically impracticable;

- the signal acquisition and treatment systems in these meters use proprietary electronics and software that are difficult to be audited and validated from the perspective of legal metrology, jeopardizing the transparency and reliability of flow measurement results;

- due to the large dimensions of the conduit, some types of flowmeters use the technique of sampling flow velocities only at a specific point in the pipe cross-section or only in one or two paths through the flow, inferring the water flow rate based on that flow velocity sample, simply neglecting the possibility of occurrence of flows with asymmetric velocity profiles or with the presence of flow swirl;

- the criteria considered by users in the implementation of a water measurement system in large pipelines often consider only the costs of the initial investment, without assessing the costs of operating the meter, without guaranteeing the availability of spare parts and technical assistance services and without ensuring the metrological traceability of measurement results during the many years of meter operation.

2. Pitometry technique

Considering the worrying issues presented previously, the Fluid Flow Laboratory of IPT-Instituto de Pesquisas Tecnológicas, a technological research institute in Brazil, developed a methodology for measuring water flow in large conduits based on the fundamental technique of pitometry and using the Cole type Pitot tube for mapping the flow velocity profiles in the pipes.

2.1 Cole type Pitot tube

Basically, the Cole type Pitot tube is a differential pressure probe designed by Edward Cole around 1896 [1] and is composed of two parallel tubes of approximately 6 mm outside diameter, bent at a 90º angle and oppositely oriented at the ends. The Cole type Pitot tube is shown in Figure 1.

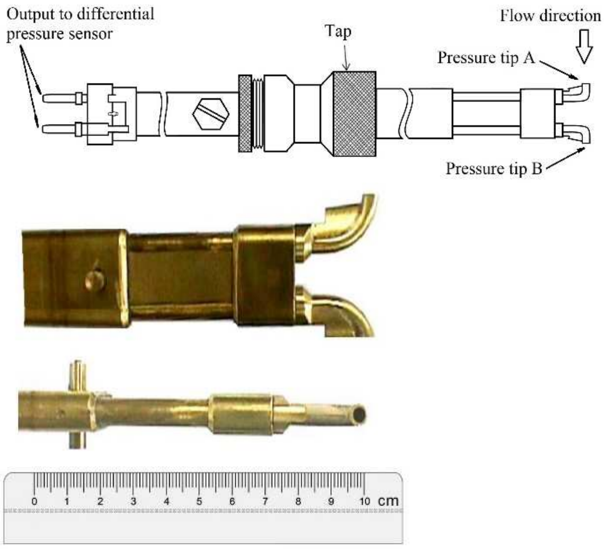


Figure 1: The Cole type Pitot tube.

One pressure tip is in the front position to the flow path of the liquid and the other in the opposite position. The front tip to the flow (tip A) measures the total pressure and the other (tip B) measures the pressure of the wake flow, defining a differential pressure signal measured by pressure transducers and that is proportional to the square of the flow rate of the liquid.

As shown in Figure 2, in the measurement of water flow rates in large pipes it is common to use a modified Cole-type Pitot tube which has a safety pin located in between the tips to protect them from possible damage caused by their impact against the internal wall of the pipe during insertion of the probe.

Figure 2: Photograph of a modified Cole type Pitot tube with a safety pin in between the tips.

2.2 Cole type Pitot tube calibration

At IPT, the Cole type Pitot tubes are calibrated using an aerodynamic wind tunnel as shown in Figure 3.

Figure 3: Calibration of Cole type Pitot tube in the aerodynamic wind tunnel at IPT Fluid Flow Laboratory.

Tests conducted at IPT using a wind tunnel and a large towing tank showed that Cole type Pitot tubes can be calibrated in air flows and used in water flows, provided that the Reynolds number similarity is respected [2].

During calibration, the Cole type Pitot tube is positioned at the central area of the wind tunnel discharge section, avoiding the regions near its internal walls. A conventional L-type Pitot-static tube is used as a reference air velocity probe. Both Pitot tubes are connected to pressure transducers and two rising sequences of points consisting of ten air flow velocities between 5 m/s and 36 m/s are compared. Based on Reynolds numbers similarity, where

$$Re_{water} = Re_{air} \quad (1)$$

these air flow velocity limits correspond to water flow velocities of 0.3 m/s and 2.4 m/s, respectively.

The mean calibration coefficient recommended by the literature for conventional Cole type Pitot tubes, including corrections, is 0.8696 [2]. Figure 4 presents a set of measurements that are commonly used by water utility companies in Brazil [3]. This figure shows the dependence of calibration coefficient (C_c) of the Cole type Pitot tube to the flow Reynolds number. The Reynolds number is defined as:

$$Re = \frac{V\,L}{\nu} \qquad (2)$$

where V is the fluid flow velocity in m/s, L is a characteristic length, here fixed as 1 m, ν = 1.004 x 10^6 m/s^2 is the kinematic viscosity of water at 20 °C.

The results shown in Figure 4 for 5 x $10^5 \le Re \le 3$ x 10^6, correspond to a water flow velocity range of 0.5 m/s $\le V \le$ 3.0 m/s. In this velocity range, the calibration coefficient of the Cole type Pitot tube varies between 0.883 for 0.5 m/s and 0.861 for 3.0 m/s with a mean value of 0.867.

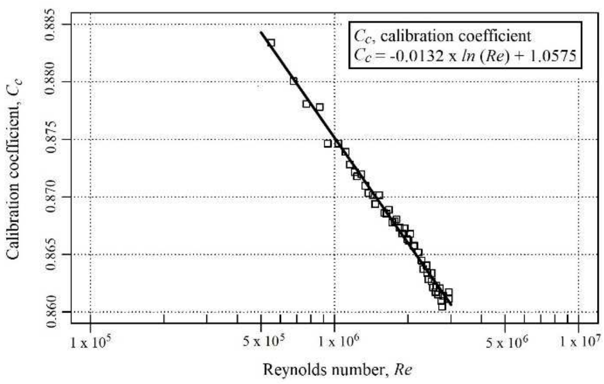


Figure 4: Reynolds number dependence of calibration coefficient (C_c) of Cole type Pitot tubes according to reference [3].

The calibration coefficient of the Cole type Pitot tube is obtained using the following equation:

$$C_c = C_s \sqrt{\left(\frac{\Delta P_s}{\Delta P_c}\right)} \qquad (3)$$

where C_s = 0.997 is the calibration coefficient of the L-type Pitot-static tube used as a standard [4], ΔP_s and ΔP_c are, respectively, the differential pressures obtained by the L-type Pitot-static tube and Cole type Pitot tube.

2.3 Flow velocity profile

For the determination of the water flow rate, the guidance of the technical standard ISO 3966 [5] is followed for the calculation of the mean flow velocity in the cross section of the pipe using Cole-type Pitot tube and the *log-linear* method for the mapping of the flow velocities at eleven points distributed along the conduit measuring diameter.

In Figures 5 and 6, respectively, the pitometry taps are shown in the outside perimeter of the pipe and the eleven measurement positions along the measuring diameter with respect to the reference dimension *h*, whose numbering starts at the point of the traverse closest to the tap and ends at the diametrically opposite point.

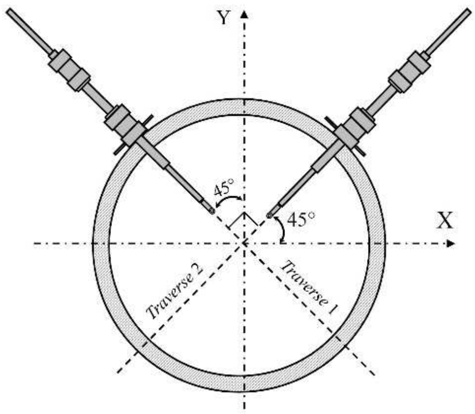


Figure 5: Position of the taps for mapping the flow velocity profile along two diameters arranged perpendicularly to each other.

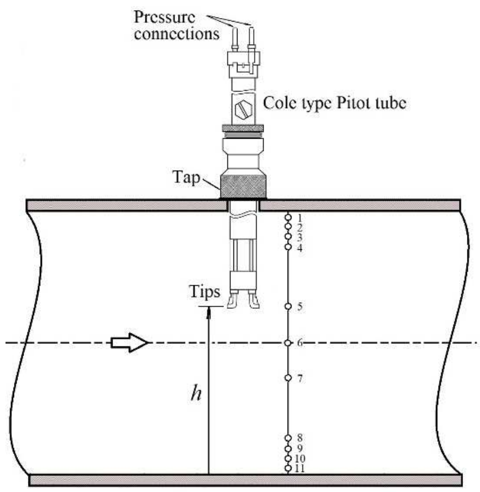


Figure 6: Positions of velocity measurement points along the traverse.

Figure 7 shows an example of water flow velocity profile including the eleven velocity measurement points.

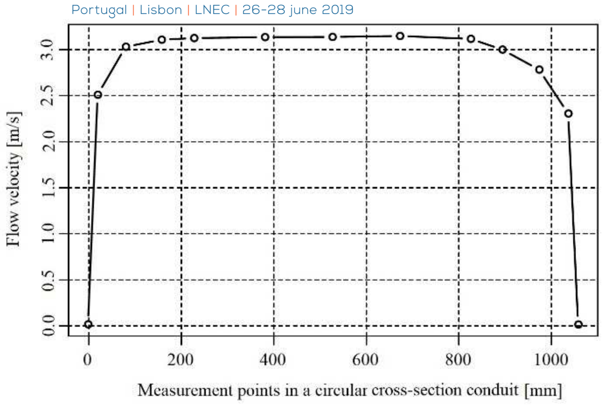


Figure 7: Water flow velocity profile determined by mapping the flow velocities at eleven points along the conduit measuring diameter.

2.4 Volumetric flow rate calculation

The volumetric flow rate of water (*Q*) in the conduit is calculated as a function of the average flow velocity ($\overline{V}$) in the measuring section and the internal cross-sectional area (*S*) of the measurement location. That is:

$$Q = \overline{V} \cdot S \tag{4}$$

where:

$$\overline{V} = C_c \cdot \frac{\sum_{i=1}^{n} \sqrt{\frac{2 \cdot \Delta P_i}{\rho_o}}}{n} \tag{5}$$

and:

C_c calibration coefficient of the Cole type Pitot tube;

ΔP_i differential pressure measured at each point of the velocity mapping, disregarding the central point on the pipe axis (point 6);

ρ_o water density under measurement conditions, considered equal to $\rho_{o,25°C} = 997{,}043$ kg/m³ .

The volumetric water flow rate can also be calculated from the flow velocity at the central point in the measurement section (V_C), the average velocity factor (*VF*) and the internal cross-sectional area of the measurement site (*S*). That is:

$$Q = VF \cdot V_C \cdot S \tag{6}$$

where:

$VF = \dfrac{\dfrac{\sum_{i}^{n} \sqrt{\Delta P_i}}{n}}{\sqrt{\Delta P_c}}$ is the mean velocity calculation factor, particular of the flow and valid exclusively for the specific pipe, with its singularities near upstream and downstream of the pitometric station and characteristic Reynolds number range. This is an empirical correlation for the calculation of the integral of Karman's law (law of power);

ΔP_c is the differential pressure measured with the Pitot Cole tube at the central point in the axis of the pipe.

2.5 Instrumentation scheme

The methodology developed and applied by IPT allows the monitoring of the signal of a flow meter present in series in the same pipeline during the process of mapping the velocity profile, as shown in Figure 8. This makes it possible to simultaneously perform the calibration of the flowmeter and make corrections of possible flow fluctuations that may occur during measurements.

Figure 8 shows the instrumentation scheme used for the mapping of flow velocity profiles established in the measurement section of the pipe.

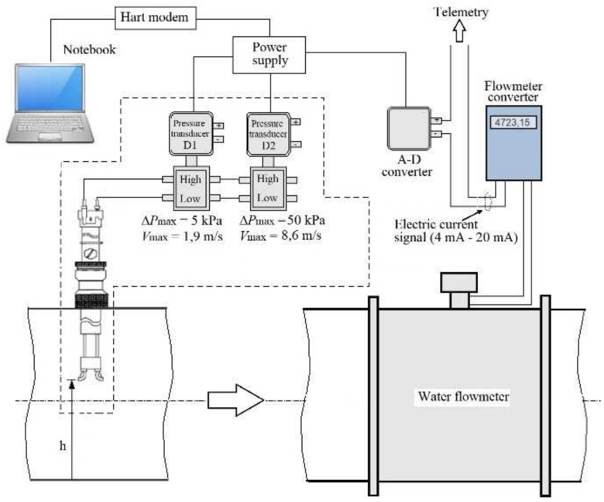


Figure 8: Scheme of the instrumentation used for the mapping of flow velocity profiles using the pitometry technique.

3. Case study

To illustrate the application of the method of water flow measurement by pitometry technique in large diameter pipelines, a case study involving the calibration of a water flow measurement system is presented below.

3.1 Description of the installation

Figure 9 shows the scheme of a water pumping station which operates with two axial hydraulic pumps of same size in parallel. In the discharge pipeline of 2232 mm internal diameter, made in steel, there is installed a dual path transit time ultrasonic flowmeter with two pairs of transducers which needed to have its metrological performance evaluated.

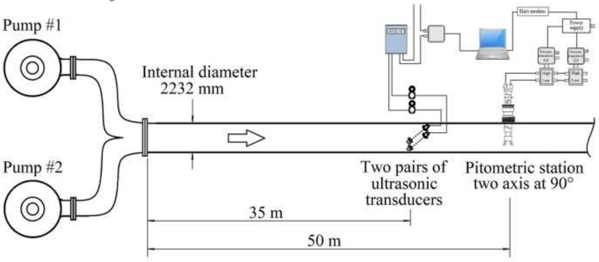


Figure 9: Sketch of the pumping station discharge pipeline, indicating the installation locations of the ultrasonic flow meter transducers and the pitometric station.

The water flow measurements were performed by applying the pitometry technique using two Cole type Pitot tubes mounted perpendicularly to each other and transversely to the longitudinal axis of the conduit through two special insertion connections, commonly known as taps.

To perform the calibration of the indication of the ultrasonic flow meter of the pumping station, in parallel to the measurement of water flow rate with Pitot tubes, the data acquisition of the flow rate indication of the ultrasonic meter was performed. For that, a data logger was installed in series at the output of the electrical signal (4 mA to 20 mA) of the ultrasonic meter sent to the supervisory system installed in the control room of the pumping station.

In the following items, the results obtained in the survey of the flow velocity profiles, the pump flow monitoring and the ultrasonic meter calibration are presented.

3.2 Results of flow velocity profiles mapping

Figures 10 and 11 show the graphs of the instantaneous flow rates measured with the pitometry technique, in two 90° diameters, and the flow rates indicated by the ultrasonic meter during the measurements performed in the pumping station discharge pipeline, respectively, only with the pump #1 in operation and with the pumps #1 and #2 in parallel.

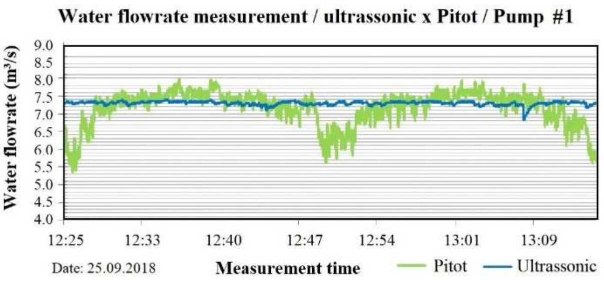


Figure 10: Water flow rates measured by the ultrasonic meter versus pitometry, only with the pump #1 in operation.

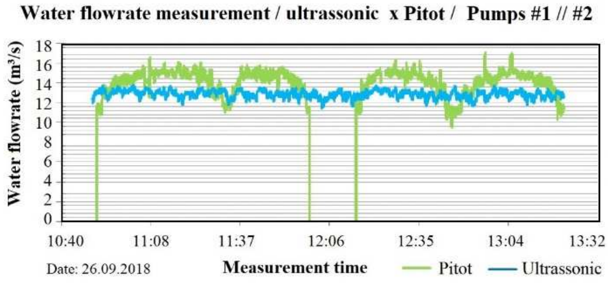
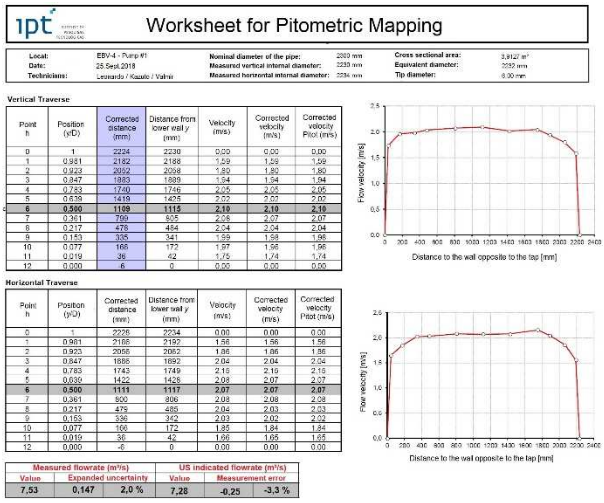


Figure 11: Water flow rates measured by the ultrasonic meter versus pitometry, with pumps #1 and #2 operating in parallel.

Figures 12 and 13 show the results sheets of the pitometry mapping performed on the discharge pipe of the pumping station, respectively, for the case of operation only with pump # 1 and for pumps # 1 and # 2 operating in parallel.



Worksheet for Pitometric Mapping

Local:	EBV-4 - Pump #1	Nominal diameter of the pipe:	2300 mm	Cross sectional area:	3,9127 m²
Date:	25.Sept.2018	Measured vertical internal diameter:	2230 mm	Equivalent diameter:	2232 mm
Technicians:	Leonardo / Kazuto / Valmir	Measured horizontal internal diameter:	2234 mm	Tip diameter:	6,00 mm

Vertical Traverse

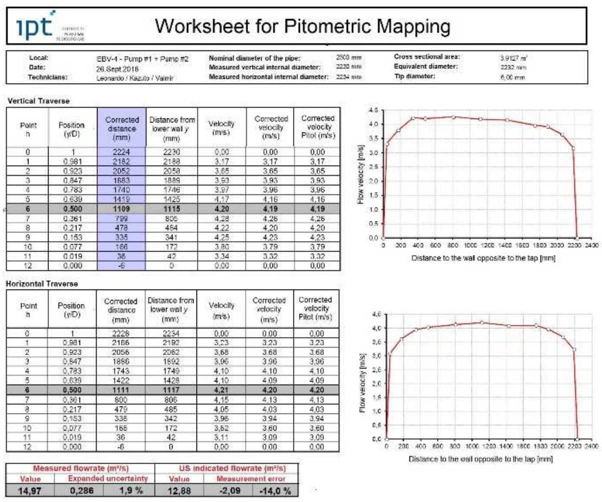
Point h	Position (y/D)	Corrected distance (mm)	Distance from lower wall y (mm)	Velocity (m/s)	Corrected velocity (m/s)	Corrected velocity Pitot (m/s)
0	1	2224	2230	0,00	0,00	0,00
1	0,981	2182	2188	1,59	1,59	1,59
2	0,923	2052	2058	1,80	1,80	1,80
3	0,847	1883	1889	1,94	1,94	1,94
4	0,783	1740	1746	2,05	2,05	2,05
5	0,639	1419	1425	2,02	2,02	2,02
6	**0,500**	**1109**	**1115**	**2,10**	**2,10**	**2,10**
7	0,361	799	805	2,08	2,07	2,07
8	0,217	478	484	2,04	2,04	2,04
9	0,153	335	341	1,99	1,98	1,98
10	0,077	166	172	1,97	1,96	1,96
11	0,019	36	42	1,75	1,74	1,74
12	0,000	6	0	0,00	0,00	0,00

Horizontal Traverse

Point h	Position (y/D)	Corrected distance (mm)	Distance from lower wall y (mm)	Velocity (m/s)	Corrected velocity (m/s)	Corrected velocity Pitot (m/s)
0	1	2228	2234	0.00	0.00	0.00
1	0,981	2186	2192	1,56	1,56	1,56
2	0,923	2056	2062	1,86	1,86	1,86
3	0,847	1886	1892	2.04	2.04	2.04
4	0,783	1743	1749	2,15	2,15	2,15
5	0,639	1422	1428	2,08	2,07	2,07
6	**0,500**	**1111**	**1117**	**2,07**	**2,07**	**2,07**
7	0,361	800	806	2,08	2,08	2,08
8	0,217	479	485	2,04	2,03	2,03
9	0,153	336	342	2,03	2,02	2,02
10	0,077	166	172	1,85	1,84	1,84
11	0,019	36	42	1,66	1,65	1,65
12	0,000	-6	0	0.00	0.00	0.00

Measured flowrate (m³/s)			US indicated flowrate (m³/s)		
Value	Expanded uncertainty		Value	Measurement error	
7,53	0,147	2,0 %	7,28	-0,25	-3,3 %

Figure 12: Pitometric data and flow velocity profiles in the discharge pipeline of the pumping station operating only with pump #1.



Worksheet for Pitometric Mapping

Local:	EBV-4 - Pump #1 + Pump #2	Nominal diameter of the pipe:	2300 mm	Cross sectional area:	3,9127 m²
Date:	26.Sept.2018	Measured vertical internal diameter:	2230 mm	Equivalent diameter:	2232 mm
Technicians:	Leonardo / Kazuto / Valmir	Measured horizontal internal diameter:	2234 mm	Tip diameter:	6,00 mm

Vertical Traverse

Point h	Position (y/D)	Corrected distance (mm)	Distance from lower wall y (mm)	Velocity (m/s)	Corrected velocity (m/s)	Corrected velocity Pitot (m/s)
0	1	2224	2230	0,00	0,00	0,00
1	0,981	2182	2188	3,17	3,17	3,17
2	0,923	2052	2058	3,65	3,65	3,65
3	0,847	1883	1889	3,93	3,93	3,93
4	0,783	1740	1746	3,97	3,96	3,96
5	0,639	1419	1425	4,17	4,16	4,16
6	**0.500**	**1109**	**1115**	**4,20**	**4,19**	**4,19**
7	0,361	799	805	4,28	4,26	4,26
8	0,217	478	484	4,22	4,20	4,20
9	0,153	335	341	4,25	4,23	4,23
10	0,077	166	172	3,80	3,79	3,79
11	0,019	36	42	3,34	3,32	3,32
12	0,000	-6	0	0,00	0,00	0,00

Horizontal Traverse

Point h	Position (y/D)	Corrected distance (mm)	Distance from lower wall y (mm)	Velocity (m/s)	Corrected velocity (m/s)	Corrected velocity Pitot (m/s)
0	1	2228	2234	0,00	0.00	0,00
1	0,981	2186	2192	3,23	3.23	3.23
2	0,923	2056	2062	3,68	3.68	3.68
3	0,847	1886	1892	3,96	3.96	3,96
4	0,783	1743	1749	4,10	4.10	4,10
5	0,639	1422	1428	4,10	4.09	4,09
6	**0,500**	**1111**	**1117**	**4,21**	**4.20**	**4,20**
7	0,361	800	806	4,15	4.13	4,13
8	0,217	479	485	4,05	4.03	4,03
9	0,153	336	342	3,96	3.94	3.94
10	0,077	166	172	3,62	3.60	3.60
11	0,019	36	42	3,11	3.09	3,09
12	0.000	-6	0	0,00	0.00	0,00

Measured flowrate (m³/s)			US indicated flowrate (m³/s)		
Value	Expanded uncertainty		Value	Measurement error	
14,97	0,286	1,9 %	12,88	-2,09	-14,0 %

Figure 13: Pitometric data and flow velocity profiles in the discharge pipeline of the pumping station operating with pumps #1 and #2 in parallel.

Figure 14 shows the measurement errors determined in the calibration of the ultrasonic flow meter at the two-pump station operating flow rates.

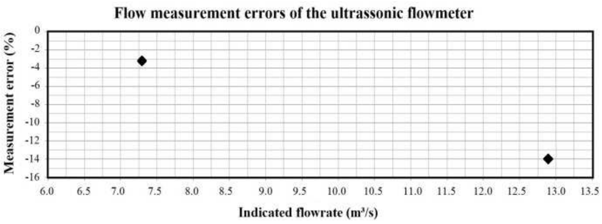


Figure 14: Flow measurement errors presented by the ultrasonic meter.

The information and data of the measured parameters recorded during the measurements indicated that the uncertainties associated with the measured values were of the order of 2.0 % of the water flow rate measured by means of the pitometry technique, which is fully compatible with the conditions and difficulties resulting from the measurement of water flow in the field in a large conduit.

4. Conclusion

Based on the good results obtained in a large number of applications in closed conduits of raw and treated water together with water production, transportation and distribution companies, the fundamental and auditable technique of pitometry has shown to be a quite appropriate tool for validation of water flow measurement in large diameter pipelines. That is, the pitometry technique allows recalibration of the flow meters within the periodicity established in the metrological regulations without the need to removal the flow meter from its field operation site. In addition, it is not necessary to know and dominate the acquisition and signal processing technology used by these meters since the end result of the measurement system as a whole is validated to ensure the reliability of flow measurement results. Likewise, the effects of installing the meter, the conditions of the water flow in the conduit and sampling the flow velocity only at a specific point in the cross section of the tube (in the case of point velocity meters) or only in one or two trajectories through the flow (in the case of transit time ultrasonic meters) are solved. Finally, the metrological traceability of measurement results can be guaranteed during the many years of meter operation. However, although the uncertainties associated with the results of the measurements performed by applying the pitometry technique are greater when compared to those obtained in calibrations of water flow meters in a laboratory test bench, they can be improved with the technical standardization of the shape and dimensions of the Pitot tubes, by improvement of the calibration methods of the probes and by using techniques of mathematical modelling of the flow.

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