Comparison of two different methods for calibration of Cole type Pitot tubes

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Abstract

The Cole type Pitot tubes (Pitot-Cole tubes) are widely used by water utility companies to map fluid flow velocity profile and thus measure the flow rate in pipelines. This technique is mainly used for on-site calibration of other kind of flow meters, such as electromagnetic or ultrasonic, particularly when removing the meter from the pipeline is somehow not feasible. Therefore, when using Pitot-Cole tubes for those purposes, the determination of the calibration coefficient (C_d) and its associated uncertainty contributes significantly to the results of such measurements.

This paper presents the description and comparison between the results of two different methodologies for calibration of Pitot-Cole tubes: in a wind-tunnel and in a towing tank. Comparisons were also performed for two configurations of the Pitot-Cole tube, with and without a central pin between the two pressure tips, in which the inclusion of this feature increases the measured differential pressure, leading to a set of more reliable measurements.

The obtained results demonstrate coherence and feasibility of the wind-tunnel calibration for normalized Reynolds numbers (Re/L) greater than 7×10^5. These results also show that a more precise value can be applied along distinct velocity ranges, individually for each Pitot-Cole tube, instead of employing the usual value of $C_d = 0.869$, used since Cole proposed this form of Pitot tube in 1896. Another major result shows that, for lower values of Re/L, a correction of the calibration coefficient is needed, in order to reduce the uncertainty associated to the measurement. This second result is especially important since the corresponding velocities are related to lower flow rates, in which their measurements are usually followed by larger uncertainty estimates.

1. Introduction

Water distribution systems are strictly dependent on well calibrated equipment, especially when considering the measurement of its main resource: water. To correctly measure its flow through the system, flow meters must be regularly calibrated over time. One such method for calibration of flow meters is based on the so called Cole type Pitot tube (Pitot-Cole tube or also reversible pitometer, as it used to be called).

In order to guarantee the results of the aforementioned calibration method, the Pitot-Cole must also be calibrated and in doing so, the problem of the insertion of the Pitot rod into the flow arises, creating significant disturbances to the velocity profile which is being measured. The shape of the tips and the use of a hydrodynamic profile that incurs in drag reduction, induces flow effects close to the tips that need to be mitigated by the use of a calibration coefficient, denoted here by C_d. Such coefficient can be described as a ratio of actual average velocity to the measured fluid velocity at a certain position of the Pitot-Cole tube inside the flow.

In Brazil, in the early 2000s, Pitot-Cole tubes were rarely calibrated, and until then, the C_d was usually adopted as equal to 0.869, as it was proposed long ago by Edward S. Cole [1]. However, due to numerous reasons, such as, the need of increasing reliability in measurement data, dimensioning of the catchment system and distributions to meet the continuous growth of demand, monitoring for determination of loss rates, measurement traceability requirements for proving metrological reliability, accreditation of conformity assessment bodies and meeting normative requirements applied to laboratory quality management systems, the calibration of this type of instrument has become more relevant.

One of the methodologies for experimental determination of the C_d coefficient for this type of Pitot tube is by means of towing tank measurement, which is considered a relatively costly method (see [4]). In order to meet this demand, the Institute of Technological Research of the State of São Paulo (IPT) developed and proposed an economically more feasible methodology for calibration using the normalized Reynolds number correlation (Re/L) so the calibration procedure could be carried out in a wind-tunnel [4].

In this work, these two different methodologies for obtaining the mentioned calibration coefficient are evaluated and have their results compared: in a wind tunnel and in a towing tank facility. Such methods are much used in this field and, therefore, are worth being evaluated. Also, two types of Pitot-Cole tubes are compared: with or without a central pin between the two reversible tips, a feature that increases the wake and provides better readings of velocities.

The attained results show reasonable agreement between the two methods for $Re/L > 5\times10^5$, a result that agrees with previous works. One interesting result is presented for values of $Re/L < 5\times10^5$ and for $Re/L > 2.5\times10^6$: As Edward S. Cole proposed, the value of the calibration coefficient can be adopted as constant, although it might differ slightly for each individual instrument and also for slightly different designs, such as the introduction of the central pin.

2. The Cole type Pitot tube

2.1 Brief Historical Background

The Pitot-Cole tube, depicted schematically in Figure 1 and in detail in Figure 2, dates back to 1896, and it was proposed by Edward S. Cole [1] as a way to determine flow velocity along a large pipe by measuring the differential pressure at specific radial positions at as many diameters as one might need to measure. By employing this method, it is possible for one to establish a discrete but detailed sample of the velocity profile of the flow. It has been shown, in many other works (see [1], [2] and [3], for example) that, if conducted carefully, in a steady flow condition, even with only one mapping traverse of the velocity profile, this measurement can be used to calibrate other flow meters with reasonable accuracy.

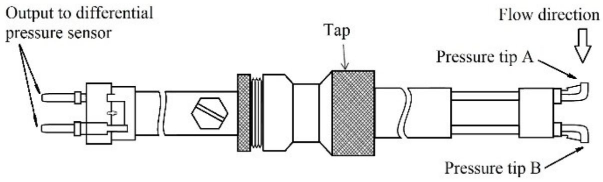

Figure 1: The Cole type Pitot tube - Schematic representation.

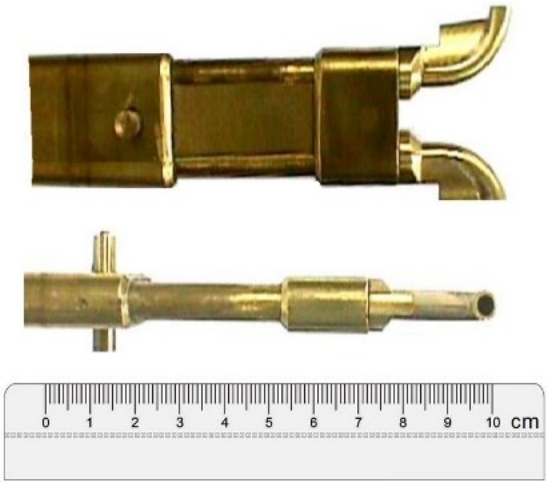

Figure 2: The Cole type Pitot tube – Detail of tips.

Albeit its age, it is a fairly conventional and robust method of calibration of flow meters, as it is suitable for on-site usage, it is easy to transport, and can be easily applied in a varied range of pipe diameters and fluid velocities, having also the advantage of low uncertainty level associated to its measurements in such harsh conditions of work. Also, it is a relatively affordable equipment, when compared to other flow meters or even with the costs required for laboratory calibration of the often large flow meters installed in water supply systems.

It sure have a few disadvantages, such as not being an automatic flow meter, which calls for the operation of a specialized technician and requires the addition of pressure transmitters connected to a computer. Another issue is that it needs to be inserted in the flow, a condition that requires a tap with a valve to be installed outside the pipe, usually close to the flow meter being calibrated.

Although this later question does not represent a major problem in terms of implementation, it leads to a more relevant matter that needs to be addressed: the inherent disturbance of the velocity profile by the insertion of the Pitot-Cole rod into the flow. As stated before, to correct the influence of the Pitot-Cole tips, a calibration coefficient, C_d, is applied to the measurements through the following relation:

$$V_0 = C_d\sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

Where V_0 is the measured fluid velocity, ΔP is the differential pressure read from the tips of the Pitot-Cole tube in each traverse position and ρ is the density of the fluid. The value of C_d is obtained in different ways depending on the calibration method and this will be detailed further ahead in this paper.

2.2 Effects of the Instrument Calibration

Acknowledging the issue of measurement deviation, Cole and Hubbard, respectively in [1] and [2], carried out the first experiments to estimate values of C_d in order to correct the measurements made when using the Pitot-Cole tube. The experiments were conducted at different facilities, providing a detailed study on the influence of a variety of pipe diameters and the smoothness of the velocity distribution in those conduits. At that work, it was concluded that the accuracy of the measurements was highly dependent on the calibration coefficient and that this value could be found by calibrating the Pitot-Cole tube at a location in which "the velocity distribution or disturbance is similar to that at the location in which the velocity distribution is to be determined" [1]. Tests conducted in different conditions, such as in distinct pipe diameters and in a revolving boom station, concluded that the mean value of C_d was around 0.869, but no detailed conclusions in relation to its dependency on Reynolds number was draw.

As it is expected, the physical simulation of disturbances for large pipes in a controlled environment is costly and almost a custom implementation that makes the calibration of Pitot-Cole tubes impractical. A closer method, however, is to calibrate the Pitot-Cole tube in a towing tank, simulating the flow velocities by imposing it to the instrument along the tank. Similar to that is the usage of a circular tank, as presented in [2] and [7]. Using these methods, it is possible to obtain values of C_d for a range of flow velocities in which the water distribution systems actually operate.

As presented in [4], mainly due to the lack of availability of facilities and the costs associated with the usage of a towing tank, a new methodology was proposed at IPT – Institute for Technological Research, in Brazil, in the early 2000s. At that work, it was shown that the calibration of a Pitot-Cole tube, similarly to the calibration of a "S" type Pitot tube, could be performed in a wind tunnel and that, for $Re/L > 5\times10^5$ (equivalent to 0.5 m/s in water), the obtained calibration coefficient is suitable to be used in water for on-site calibration of flow meters. This is possible due to the Reynolds similarity relation, $Re_{water} = Re_{air}$, in which velocities of air from 5 m/s to 36 m/s can be mapped, respectively, to 0.3 m/s and 2.4 m/s in water. Also, for the mentioned range of Re/L, the authors concluded that the collected data showed good agreement between the calibration coefficient values obtained from the wind tunnel and from the towing tank experiments. It was noted that there are some advantages in the proposed methodology as well, such as, greater stability of readings, easily attainment of flow rate set point, assembling of the instruments for the tests, faster calibration process and no need for transducer purges.

Another important result from [4] is that the tests indicated that the periodic calibration of Pitot-Cole tubes was in great need, since it was observed that minor changes in geometry of the tips, usually occurring from the usage of the instrument, could lead to a difference of up to 5% in C_d values. Because of this result, it was recommended to identify the tip in use, since flow direction can be read from both sides of the tube, using tip A or B (see Figure 1), and their C_d values can vary significantly. The authors of [5] even conclude, from a statistical analysis of a set of individual calibrations of Pitot-Cole tubes that, the use of different sides of the same tube is equivalent to completely different tubes, since their C_d values vary greatly.

The influence of this variation is deeper evaluated in [5] through the statistical analysis of a historical database o calibration coefficients obtained from nine years of experiments at IPT. They concluded that a single mean value for C_d for all Pitot-Cole tubes can have a large impact on the uncertainty of the flow rate measurement (up to 1.5%). At that same study, it is presented a figure of 3.5×10^7 m³/year of uncertainty in the measurement of water distributed in the metropolitan area of São Paulo, in Brazil. Also, the authors recommend the periodic calibration of each Pitot-Cole tube, despite of no significant changes on the mean value of C_d being found over that period of time.

This last reference was also influenced by the results presented in [6], in which the authors state that one of the major contributions to the overall uncertainty is given by the uncertainty of C_d. Apart from the fact that the study encompasses only the "S" type Pitot tube, it is known from the literature presented above that this is also a main issue for the Cole type Pitot tube. Another investigation carried out in that study is the influence of the Reynolds number on the calibration coefficient of that kind of Pitot tube, to which the authors concluded that this effect is negligible when compared to the total uncertainty of the flow rate measurements. In contrast, the effect of the manufacturing quality was found to be relevant, which shows that an individual calibration of Pitot tubes is always preferred, as concluded by [5].

Taking into account the conclusions and results presented by the references previously cited, this paper aims at the investigation of the influence of a specific range of Reynolds numbers on the values of C_d, employing two configurations of Pitot-Cole tubes, in two different methods of calibration. The main purpose of this study is to reduce the uncertainty on the flow rate measurements performed on-site, since the impact of this is clearly of great importance for natural resources sustainability, such as the rational use of water.

3. Methodology

A set of four Pitot-Cole tubes was employed in this study. Two of them, here denoted by C1 and C2, are built as the tube presented in Figure 2. The other two, P1 and P2, are built with the inclusion of a safety pin between the tips, in order to protect them when in operation, since they can easily break off when touching the pipe walls. This modified version, presented in Figure 3, is the one preferred at IPT for on-site flow meter calibration, since it is more secure to use it on the field.

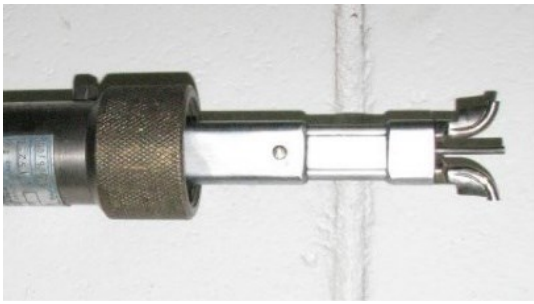

Figure 3: Modified Cole type Pitot tube with a safety pin between tips.

In order to compare the results, the dimensionless Reynolds number is used, divided by an unitary diameter (Re/L). The calibration methods are described in the following subsections.

3.1 Wind Tunnel Calibration

The adopted calibration procedure is the same as the one employed regularly at the IPT Fluid Flow Laboratory. An aerodynamic wind tunnel is used for the calibration of the Pitot-Cole tubes, as depicted in Figure 4. This wind tunnel was designed so that the velocity profile of the air pushed form the inside, at its test section, is uniform with low turbulence for flow velocities as high as 50 m/s.

Figure 4: Aerodynamic wind tunnel at IPT's Fluid Flow Laboratory – On the left of the test section the standard Pitot-static tube is installed and its measurements are used as reference to obtain C_d values for the Pitot-Cole tubes being tested, which are installed on the right.

By measuring the differential pressure using a conventional standard Pitot-static tube, the calibration coefficient of the Pitot-Cole tube, C_d, can be calculated from the following relation:

$$C_d = C_{Standard}\sqrt{\frac{\Delta P_{Standard}}{\Delta P_{Cole}}} \qquad (2)$$

Where $C_{Standard}$ is the calibration coefficient of the standard Pitot-static tube and ΔP_{Cole} and $\Delta P_{Standard}$ refers, respectively, to the measured differential pressure by the Pitot-Cole and the standard Pitot-static tubes.

Tests were performed for each of four Cole type Pitot tubes, for both tips of these instruments, in twenty different velocity conditions that are equivalent to Re/L values from, approximately, 2.0×10^5 to 2.3×10^6. The differential pressures of both instruments were measured using inclined column manometers and no repetition was needed, since this is the standard procedure for calibration and the readings are performed only when differential pressure stability is attained.

3.1 Towing Tank Calibration

This method of calibration of Pitot tubes is fairly traditional, although more expensive, since this kind of facility demands heavier maintenance and the tests are usually more time consuming. The procedure is pretty straight forward: one or a set of Pitot tubes (Cole type, "S" type, static or etc.) is attached to a carriage suspended over the tank and supported on rails on both sides. The carriage is then moved with constant speed along the tank, which is usually long, straight, relatively narrow and deep enough so that no waves are generated from reflexion on the walls and no effect of the bottom is significant. An overview of the towing tank of IPT with its carriage is presented in Figure 5. This facility is

250 m long, 5 m wide and its carriage can reach up to 3.2 m/s.

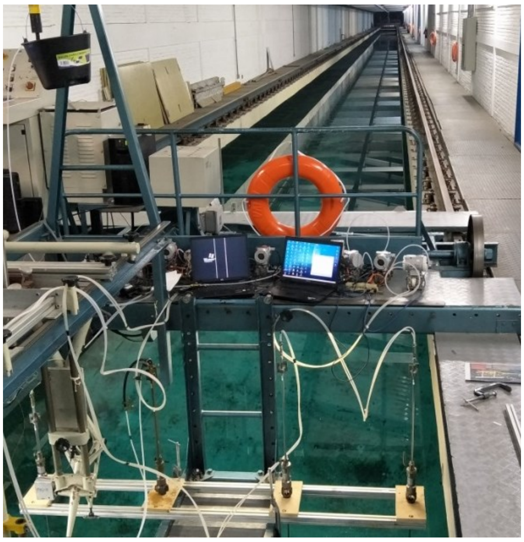

Figure 5: Overview of Towing tank facility at IPT – The Cole type Pitot tubes can be seen on the bottom, attached to a holding structure at the lower deck of the carriage.

An encoder system is adopted to register the revolutions per minute of one of the carriage's wheels, which are used to compute the velocity of the system. Similarly to expression (2), this velocity of the moving Pitot-Cole tubes is employed to calculate C_d values from eq. (3) below, computing the velocity directly from the differential pressures read with the Pitot-Cole tubes:

$$C_d = \frac{V_{Carriage}}{V_{Cole}} \qquad (3)$$

Where $V_{Carriage}$ is the velocity registered from the moving system and V_{Cole} is the velocity computed from the differential pressure measured by the Pitot-Cole tubes, with correction only for the calibration coefficients of the pressure transducers, which have very low individual contributions on the uncertainties of the flow rate measurements, being considered negligible for this study.

The experiment was carried out for 17 velocities, with a repetition of three runs for each. The velocity range corresponds to Re/L values from $1.15{\times}10^5$ to $3.4{\times}10^6$, in order to cover and outrange the values usually employed for the wind tunnel calibration of Pitot tubes. Especial attention was given to lower and higher values in this range, since the idea is to reduce the uncertainty of flow rate measurements for more extreme values of fluid velocities, in which case the velocity profile is usually disturbed and measurements can be harder to perform with relative low uncertainties. Both sides of the four Pitot-Cole tubes were tested and had their calibration coefficients computed for all the velocities of the test.

4. Results

Assuming that each side of a single Pitot-Cole tube might correspond to a completely different instrument, as stated by the authors of [5], the sample used in this study can be regarded as two sets of four instruments each: four with a central pin and four without this feature.

The results of the measurements in the towing tank are compared to those performed using the wind tunnel and the threshold of $Re/L = 5{\times}10^5$, proposed in [4], is put to a test, since the sample of that study was scarce and restricted to a limited range of Re/L values for the towing tank experiments.

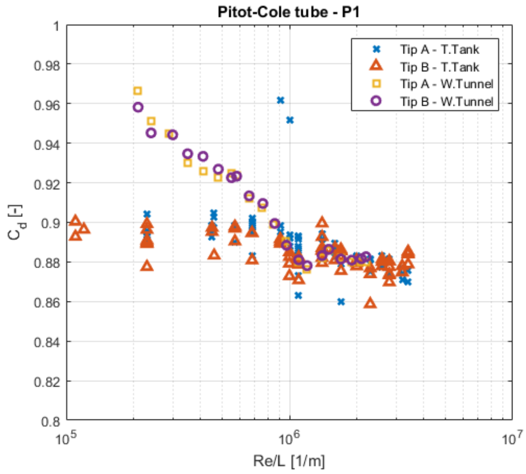

Figure 6: C_d values for Pitot-Cole P1 (with pin).

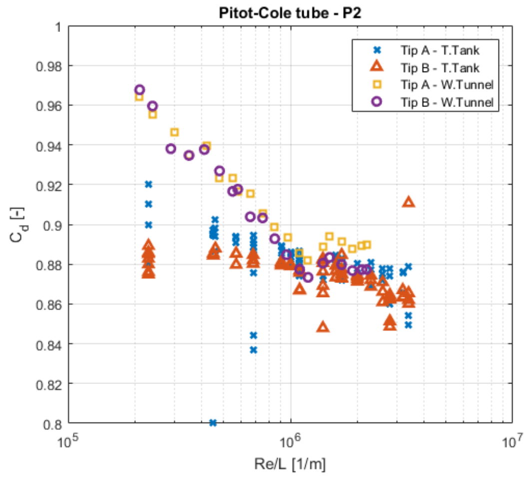

Figure 7: C_d values for Pitot-Cole P2 (with pin).

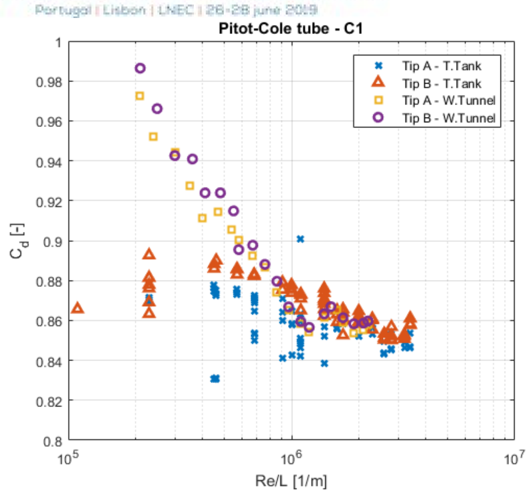

Figure 8: C_d values for Pitot-Cole C1 (without pin).

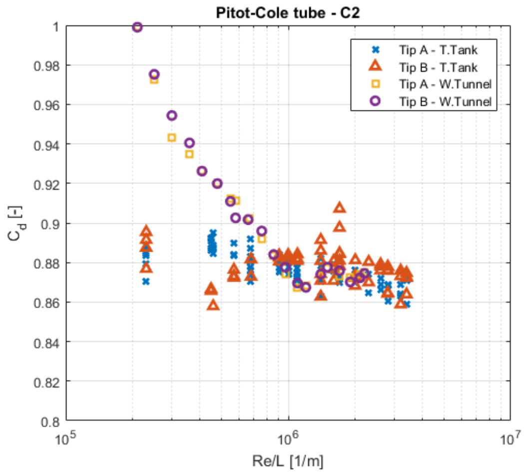

Figure 9: C_d values for Pitot-Cole C2 (without pin).

It is possible to observe from Figure 6 to Figure 9 that both methods of calibration are coherent for the expected range. Outside it, the values of C_d from the towing tank are more reliable and are in agreement with the other studies. In this figures is also shown that there is less dispersion for the data collected in the experiments with the instruments that have the central pin. As stated before, this feature increases the reliability of the readings by creating a stronger wake in the flow, and, therefore, leads to more accurate measurements.

Outliers were excluded for the analysis, so values of C_d below 0.84 and above 0.94 for the towing tank experiments are discarded for mean and standard deviation computations.

4. Conclusions

Analysis of the results without differentiation of the tips (Figure 10 and Figure 11) indicate that a mean value of C_d can be used even for low and high values of Re/L, as proposed by Edward S. Cole in [1] but, nevertheless, the coefficient must be obtained for each instrument, since the standard deviation is considerably large and the uncertainties can be greatly affected, as presented in [4] and [5]. From these scatter plots it is also visible that the mean value of the calibration coefficient for the Pitot-Cole with the pin is slightly larger than the one proposed by Edward S. Cole.

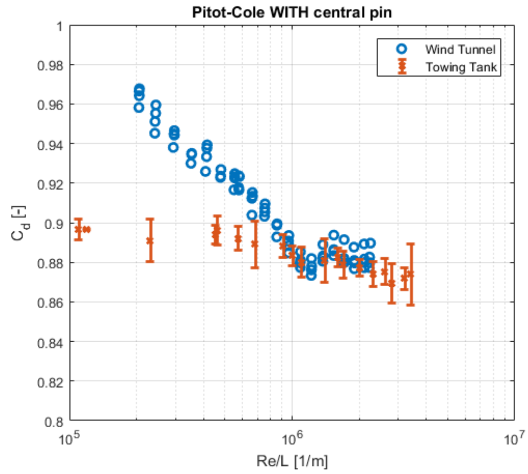

Figure 10: C_d values for both Pitot-Cole tubes with central pin - Bars indicate the standard deviation from mean values.

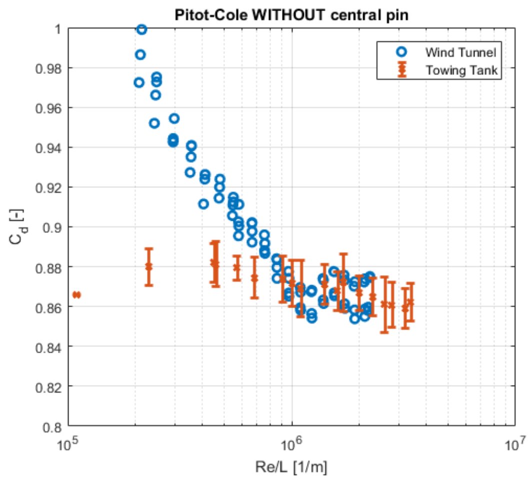

Figure 11: C_d values for both Pitot-Cole tubes without central pin - Bars indicate the standard deviation from mean values.

The attained results show good agreement with previous studies for the range $5\times10^5 < Re/L < 2.5\times10^6$. Also, in this range, both methods of calibration agree between them. An evaluation of the calibration coefficient for values of Re/L outside the mentioned range indicates that a constant value of C_d can be applied along the considered values of Re/L, but caution must be taken, since it is clear from the results that a value of C_d must be found for each instrument and preferably for each tip as well. From this experiments it is also identifiable that the Pitot-Cole provided with a central pin between tips is preferable, since its calibration coefficient values are much less sparse than the results obtained from the tube without the central pin.

Overall, the results indicate that measurements for lower flow velocities can be performed with the use of a mean value of C_d obtained from the towing tank. Unfortunately, the calibration in this range cannot be performed in the wind tunnel. However, the results confirm that it is a robust method for the most common velocities measured in water distribution systems.

Acknowledgments

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