Article

Influence of Butterfly and Gate Valves Upstream Large Water Meters

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Abstract: The research presented was conducted to quantify the effects of butterfly and gate valves located upstream water meters with diameters larger than 50 mm. Errors caused by these valves can have an enormous financial impact taking into consideration that a small percentage of variation in the error of a large meter is typically related to a significant volume of water. The uncertainty on the economic impact that a valve installed upstream of a medium size water meter leads to many water utilities to oversize the meter chambers in order to mitigate the potential negative errors. Most manufacturers approve their meters for a specific flow disturbance sensitivity class according to the standard ISO 4064-1:2018. Under this classification, a correct operation of the meters requires a certain length of straight section of pipe upstream the meter. However, this classification of the meters cannot consider all types of flow perturbances. For this study, two types of valves, butterfly and gate, were tested upstream ten brand-new water meters from six different manufacturers constructed in four different metering technologies: single-jet, Woltmann, electromagnetic and ultrasonic. In each meter unit was tested at five flow rates, from minimum to the overload flow rates. The tests were conducted with valves set in different orientations, closing degrees, and upstream distances from the water meters under study. The research shows that the valves used can produce significant deviations in the measuring errors with respect the errors found for undistorted working conditions.

Keywords: large water meter; single-jet; Woltmann; electromagnetic; ultrasonic; flow measurement; butterfly valve; gate valve

1. Introduction

Reducing water loses is an essential strategy for improving the efficiency and sustainability of a water utility. Water loses have direct influence on revenues, billing, utility management, data for network planning, operational costs and utility future expansion. Two main components are part of these loses: real (physical) and apparent (commercial) [1]. On the one hand, real loses are due to leakages in distribution mains, in storage tanks and in service connections [2,3]. On the other hand apparent loses are originated by unauthorised consumption [4,5], data handling errors [6,7], and customer meter inaccuracies [8,9]. Regarding the meters inaccuracy, these are probably the most important ones among all related to apparent loses. There are several reasons why these inaccuracies occur [8]: unavoidable measuring errors (meter device inherent accuracy and/or consumption profile [10–13]), device blocking by particles, device aging [8,14] and installation [15]. Optimal replacement programs [16,17] and in situ testing [18,19] are highly recommended to prevent metering errors.

Water meter installation guidelines for different metering technologies can be found in [20–22] and more specifically for large meters in [23]. Some authors have studied different installation effects [15], effects on propeller meters [24] and pressure reducing valves location [25], but these two last works are related to domestic size water meters.

In a distinction by the total amount of consumed water volume, two types of consumers can be differentiated in supply systems: domestic, with water meters from DN13 to DN40, and non-domestic, from DN50 upwards. Most of the meters accuracy research is on domestic ones [26,27]. This research will focus on large meters, usually are small in number, but represent the big part of the registered volumes of water in supply systems [16,28–32]. For many supply systems, a five to ten percent of these large meters can account for 40 to 50 percent of the total billing [18].

The last survey conducted by the INE (Statistics National Institute) in Spain, in 2014, 30.4% of water consumption was non-domestic, with an increase of nearly 13.5% over the year 2011, and 69.6% was domestic, supposing a decrease of around 3% compared to the same year. If it is taken into account that, in some cases, domestic consumption in buildings and communities is counted with large meters (assuming also that there are cases of non-domestic supply with meters with nominal diameter smaller than 50 mm) and that non-domestic meters are growing and the domestic ones decreasing (considering that water used by agriculture for irrigation, in which mainly large meters are used for the high flow rates that are managed, has not been taken into account, being its volume 3.5 times the sum of domestic and industrial volumes), gives an idea of the importance of the volume accounted for by this type of meters which, in quantity, is much lower than domestic (Figure 1).
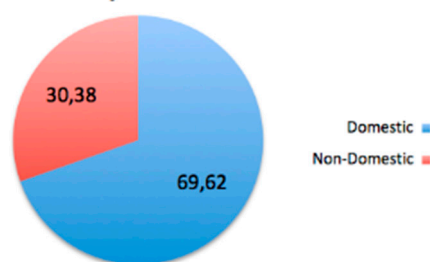

Figure 1. Domestic and non-domestic water consumption distribution in Spain in 2014.

Consequently, the aim of this document will be to determinate the errors that are being made in large meter readings based on their installation conditions, namely due to upstream flow distortion effects. To do this, tests have been carried out reproducing the conditions of the installations using the two valves mentioned above, butterfly and gate valves, which are usually found in them. These accessories were tested in different positions, openings and distances upstream the meter.

Mentioned tests have been carried out with meters from different brands and technologies. As previously mentioned, ten new water meters were tested, which used different metering technologies such as single-jet, Woltmann, electromagnetic and ultrasonic meters. Furthermore, meters came from different manufacturers, among which some of the most important brands worldwide can be found. As said, the impact of the two different valves in meters error curve and their effects, such as both over-registration and under-registration have been evaluated.

As the value and selling price of water increases, the real performance of new meters becomes a matter of concern for water utilities, farmers, domestic and industrial customers, water regulators, local governments and for all stakeholders present in the water industry. Consequently, there is an increasing need for more comprehensive, frequent and detail studies conducted from independent laboratories. The results obtained about water meters accuracy from these tests can help in improving water measurement accuracy and to decrease not only commercial losses but also physical losses in the system.

The Article is organized as follows. In Section 2, used test facility, tested water meter technologies, valves, tested flow rates, uncertainties and whole test program will be described. In Section 3, results will be presented. Several criteria will be chosen for this purpose: results regarding the valve type, regarding the water meter technology and regarding the valve arrangement (horizontal or vertical).

2. Materials and Methods

2.1. Test Bench

The aim of the research conducted is to present a set of independent tests that provide reliable information about the actual performance of brand new large diameter water meters. The tests conducted have shown significant deviations between the theoretical and the actual metrological performance found in the laboratory. These results are aligned with the conclusions raised by Neilsen et al. (2011) [26] for residential water meters in which 375 brand new residential water meters, of sizes ranging from $5/8 \times 3/4''$ to 2'', and various working principles were tested. A significant percentage of them did not meet the requirements defined in the AWWA (American Water Works Association, Denver, CO, USA) recommendations for the meter type.

The accuracy tests of the meters were carried out in a fully automated gravimetric test bench. The complete layout of the test bench is shown in Figure 2. The main features of the test bench are the following and more details can be found in [33]:

- An underground storage tank of a capacity of 50 m^3.
- The pumping station is integrated by two variable speed pumps (VSP1 and VSP2). The technical specifications for each one of the pumps are:
- VSP1: Nominal flow 250 m^3/h and 1.7 bar. Nominal power of 13.61 kW.
- VSP2: Nominal flow 109 m^3/h and 2.5 bar. Nominal power of 9.19 kW.
- A pressure vessel (PRSV) downstream the pumps, with a total volume of 350 L, reduces flow fluctuations and can also be used as water supply when testing meters at low flows, lower than 180 L/h, once the pumps have been shut down. In those cases, water pressure in the tank is controlled by means of a pressurized air system.
- The three isolation valves downstream the pressure vessel (IV1, IV2 and IV3) control the flow through the reference meters RFM1, RFM2 and RFM3. All three reference meters are electromagnetic meters connected to the control and regulation computer. The nominal diameter of the meters are 125, 25 and 6 mm respectively. A smaller fourth reference meter, 1/8'' oval gear flow meter, is located after the test sections to measure low flows (RFM4). This meter is used in combination with the smaller water tank (TNK4) to control flows up to 75 L/h.
- There are two testing sections, large testing section (LTS) and small testing section (STS). The larger one, which was the one used in this study, has a nominal inlet pipe diameter of 125 mm and is designed for testing meters with nominal diameters from 50 to 250 mm. The smaller test section has a nominal inlet pipe diameter of 50 mm and is intended for smaller meters from 15 to 40 mm. Isolation valves (IV4, IV5) control the flow through the selected test section.
- The pneumatic actuated regulating valves (RV1, RV2, RV3, RV4 and RV5) allow for the automatic adjustment of the test flow rates in each one of the tanks. Their nominal diameters are 125, 50, 15, 10 and 6 mm respectively.
- On top of each one of the reference tanks, there is a diverter in charge of recirculating water to the underground storage tank or diverting it to the gravimetric tanks. In each test, the actuating time in both directions is controlled by means of displacement switches and a precision timer.
- In order to cover for the full range of testing flow rates, the test bench incorporates four gravimetric tanks having a total capacity of 4500 L, 150 L, 12 L and 4 L respectively. The larger tank rests on four load cells, whilst the remaining three rest on a single load cell. The four tanks are equipped with calibrated weights and an automatic calibration system. A load test to guarantee the accuracy

of the load cells is carried out every month. During the calibration, the gravimetric tanks are loaded with the calibrated weights by means of pneumatic cylinders. In the case of the largest tank, as allowed in EURAMET Calibration Guide No. 18 [34] and ISO 4185:1980 [35], the weight accounts for 25% of the weighing capacity of the tank. Then, the rest of the range is calibrated replacing the weights with water and then loading the weights again according to the procedure described in "Guidelines on the calibration of non-automatic weighing instruments" EURAMET Calibration Guide No. 18 [34].

- The data acquisition and control of the test bench has been developed in LabView. All variables, including pressure, temperature, flow rate, duration of the test, weight, time of actuation of the diverters, etc. are recorded in the system and analysed. If any of the recorded parameters fall out of the admissible thresholds, the test is automatically rejected.

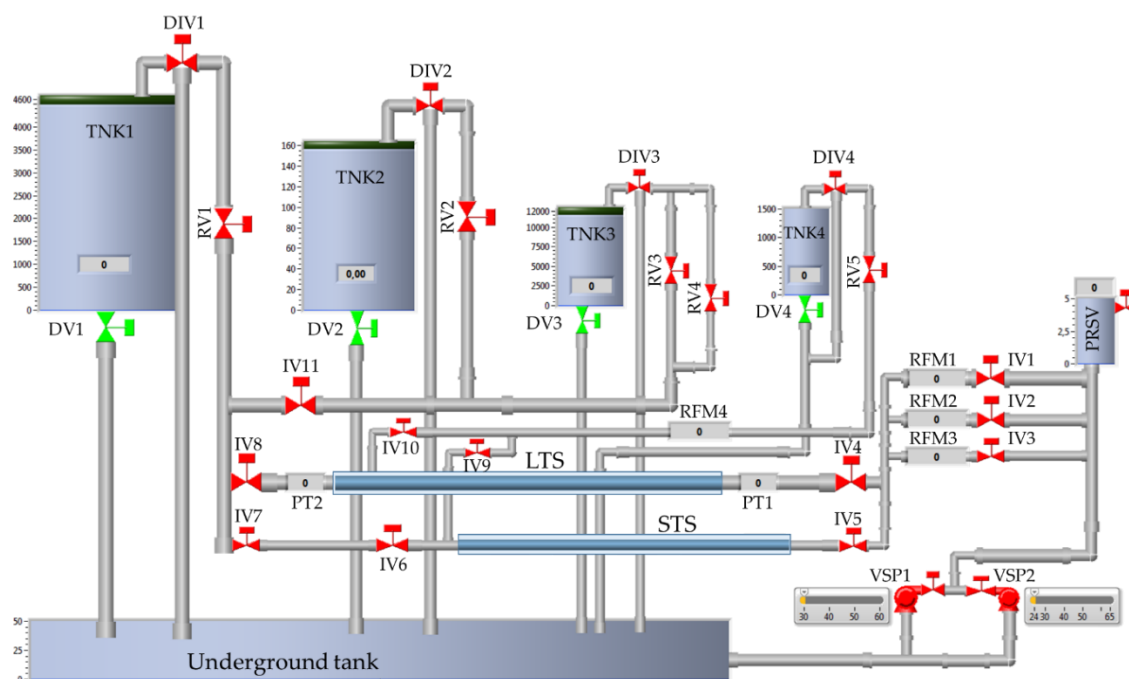More technical details about the testing facility can be found in [33].

Figure 2. Schematic of the test bench.

2.2. Testing Procedure/Protocol

The testing procedure used during the laboratory tests met all the requirements defined in [36]. In summary, the testing protocol included:

- The procedure starts with the bleeding of air from the test section and all the pipes in the test bench.
- Inputting all relevant data related to the meter and the test procedure to be used in the computer controlling the test bench. For each flow rate, the computer automatically selects the pump, reference flow meter, tank to be used and isolation valves to be actuated, as well as the opening degree required in the regulation valves.
- A proportional-integral-derivative (PID) controller stabilize the flow before the accuracy test starts. The test is initiated when the flow rate is steady and it is within the allowable limits defined in [36]. During this stage, the diverter recirculates the water to the underground tank.
- At the precise time the test starts, a picture of the dial of the meter is taken, the timer starts measuring the duration of the test and the diverter is actuated, so the water flow is poured into the tank.

- When the volume discharged into the tank reaches the defined threshold, the finalization procedure is initiated: the diverter is actuated so the water flow is recirculated to the underground tank, a picture of the meter dial is taken and the timer is stopped. The displacement time of the diverter is measured at the initiation and finalization of the test to ensure that is fast enough and equal in both directions [37].
- After a stabilization time, the computer registers the temperature and the weight of the water volume contained in the tank. The density of water is calculated based on its temperature using density tables as established in ISO 4185:1980 [35] to derive the volume passed through the meter.
- The error of the meter is obtained comparing the volume of water in the tank and the volume registered by the meter, taken from the initial and final readings of the meter.

Additionally to the above general procedure, the following requirements, established in ISO 4185:1980 [35], were also met during the tests:

- Total absence of leaks in the hydraulic circuit or liquid flow not measured through the flow diverter.
- No splashes or drips in the collection of the flow in the tanks are allowed.
- The design of the test bench does not allow the accumulation of liquid due to thermal contractions or phase changes in any section of the test bench.
- As a redundant verification, and in order to ensure the rejection of any abnormal behaviour of the test bench, the measuring error of the reference meters (RFM1, RFM2, RFM3, RFM4) are obtained for each test. If the error is out of the allowable range, defined based on the repeatability of the reference flowmeters and the test specifications, the results of the test is rejected.
- Corrections are made to account for the buoyancy caused by the air volume occupied by the water contained in the tank.
- The minimum duration of a test is, at least, 30 s [35] (p. 14). The uncertainty introduced by the flow diverter into the volume is considered negligible because its displacement times in each direction are identical within 5% and represent less than 1/50th of the total test duration [36] (p. 21) [38,39].
- The facility has a storage tank in the basement of the laboratory with a capacity of 50 m^3 of water. This storage capacity maintains the temperature range of the test water between 0.1 and 30 °C for T30 class meters [40] (p. 17). During tests, change in water temperature is less than 5 °C. The maximum uncertainty in the measurement of temperature does not exceed 1 °C [36] (p. 22).
- The test flow, as measured by the reference meters, is recorded every 40 milliseconds. At the end of the test, the highest and lowest value are reported to ensure that the relative variation of the flow rate during each test does not exceed the following requirements:

  ○ ±2.5% from Q1 to Q2 (not included)
  ○ ±5.0% from Q2 (included) to Q4

- The pressure upstream the meter does not vary during the test more than 10%. The maximum uncertainty (k = 2) in the pressure measurement is less than 5% of the measured value [36] (p. 21). The relative pressure range of water operating under nominal conditions is at least 0.3 bar, up to a maximum pressure of 5 bar at Q3 [41] (p. 42).
- This flow variation condition is acceptable if the relative variation of pressure does not exceed the following [36]:

  ○ ±5% from Q1 to Q2 (not included).
  ○ ±10% from Q2 (included) to Q4.

- As for straight sections of pipe upstream the meter, any device is installed with pipe connections having an internal nominal diameter that fits the corresponding connection of the meter and with at least 10D of straight pipe, both upstream and downstream [36] (p. 19).

- The large testing section (LTS), which is the one used for this study, has an inlet pipe of nominal diameter equal to 125 mm. Pipe reductions at the entrance and end of the test section shift the diameter from 125 mm to the same diameter as the meter under test. This way, there is a sufficient length of straight pipe upstream and downstream having the same diameter as the meter. The LTS is designed for testing meters with nominal diameters from 50 to 250 mm. The total available length from the location of the meter under test is 3650 mm upstream and 1825 mm downstream. Table 1 describes the available lengths of straight pipe upstream and downstream the meter under test for various nominal diameters.

Table 1. Distances, in pipe diameters and millimetres, of all possible combinations.

* DN (mm)	Upstream Length	Downstream Length
250	15 DN/3750 mm	7.3 DN/1825 mm
200	18 DN/3600 mm	9.1 DN/1820 mm
150	24 DN/3600 mm	12 DN/1800 mm
125	29 DN/3625 mm	15 DN/1875 mm
100	37 DN/3700 mm	18 DN/1800 mm
80	46 DN/3680 mm	23 DN/1840 mm
65	56 DN/3640 mm	28 DN/1820 mm
50	73 DN/3650 mm	37 DN/1850 mm

* DN stands for nominal diameter.

The whole process is controlled by a computer system that carries out the test automatically, registering all the data of the different variables that take part, establishing alarms and creating a report where everything is recorded. This ensures that all the parameters are within the range allowed by regulations and can be definitely concluded if the trial has been valid or not. In short, the calibration process is completely automated to avoid human errors.

2.3. Meter Sample Description

This research has mainly focused in testing those technologies commonly used for measuring water consumption in large customers. These meters are rarely tested by water utilities due to the cost of owning and operating its own testing laboratory or, alternatively, externalising the accuracy tests to an independent testing facility. However, and contrary to this cost perception it should be noted that a negative deviation of 1% of a large meter accuracy could produce enormous economic losses for the water company, higher than the costs of testing. Despite these limitations, the actual performance of new large meters is a major concern for most water companies, which can only assume that the meters they procure and install have been tested by the manufacturer and measurement errors have been properly adjusted to the company's requirements.

Unfortunately, each measuring technology is completely different and possesses its own particularities in terms of working conditions requirements and sensitivity to flow profile distortions. Even more, due to the complex relationships between flow rate, velocity distribution at the entrance of the meter and performance of the sensing element, there is not a linear relationship between the amount and type of flow distortion and the impact in the measuring errors. Consequently, the effect on the measuring errors of a valve, pipe fitting or any other element installed upstream a meter cannot be quantified in advance and can only be assessed in qualitative terms.

Table 2 shows a summary of relevant information associated to each one of the meters tested. In addition, the following sections provide a brief description of the four working principles examined in this research together with the initial accuracy curve of the meters tested.

Table 2. Summary of all tested meters and its characteristics.

Technology	Brand	Model	* DN	Flow Sensitivity	Identifier	** Q_3/Q_p (m^3/h)	Metrological Class
Single Jet	D	A	65	U0-D0	CDA65	40	315
Single Jet	E	S	65	-	CES65	20	C
Single Jet	I	F	65	U0-D0	CIF65	40	315
Woltmann	D	W	65	-	WDW65	63	100
Woltmann	E	H	65	-	WEH65	65	B
Woltmann	I	W	65	U0S	WIW65M	40	B
Woltmann	I	W	65	U0S	WIW65	40	B
Woltmann	S	M	65	U3-D3	WSM65	50	B
Ultrasonic	A	O	100	U0-D0	UAO100	100	1000
Electromagnetic	S	S	100	U5-D3	ESS100	-	

* DN stands for nominal diameter. ** Q_3/Q_p are permanent flow rates.

2.3.1. Single-Jet

These meters are widely used because of their excellent balance between metrological performance, acquisition cost and durability [42–45]. The operation is based on the tangential incidence of a single jet that drives the rotation of an impeller located inside a measuring chamber. The impeller is usually manufactured of plastic, with a lower density than water, so it floats and rests on the upper point of the bearing minimizing its wear. In most occasions, these meters are designed to work in a fully horizontal position, being the rotation axis of the impeller completely vertical. If this is not the case, the impeller is hold in a way that increases the friction and the wear and tear between moving elements, reducing the operating life of the meter.

Typically, the inlet section of single jet meter have a convergent shape, with a decreasing internal diameter. This convergent shape of the inlet section into the measuring chamber improves the velocity profile distribution so that a distorted velocity profile has as little effect as possible on the accuracy of the meter.

Three commercially available single-jet meters have been tested:

- **CDA65:** This meter satisfied ISO 4064-1:2014 standard, which is almost identical to the newer version of the standard released in 2018. The connection flanges of the meter have a nominal diameter of 65 mm. In addition, according to the manufacturer the meter has been assigned a permanent flow rate of 40 m^3/h and classified as U0-D0. This means that the meter does not require the installation of any section of straight pipe upstream or downstream in order to guarantee the accuracy against any flow profile distortion.
- **CES65:** This meter was approved following ISO 4064-1:1993 standard. The meter was classified as Class C in horizontal position with a permanent flow rate of 20 m^3/h and a nominal diameter of the connection flanges of 65 mm.
- **CIF65:** ISO 4064-1:2014 approval with a permanent flow of 40 m^3/h, a nominal diameter of the connection flanges of 65 mm and a flow profile sensitivity class of U0-D0.

2.3.2. Woltmann

The sensing element of these meters is a propeller arranged in the axial direction of the flow [12]. Woltmann meters are commonly used for bulk metering as they can stand larger working loads than other mechanical meters and newer versions have an extremely wide measuring range. Although there are three different constructions—horizontal, vertical and elbow-type—depending on the direction of the rotation axis of the propeller [20], the most commonly one used is without any doubt the horizontal type.

In this research four different brands of Woltmann meters have been tested:

- **WDW65:** Approved following the ISO 4064-1:1993 requirements. The meter has a nominal diameter of the connection flanges of 65 mm, a permanent flow rate of 63 m^3/h, and a metrological Class B.
- **WEH65:** Approved following the ISO 4064-1:1993 requirements. The meter has a nominal diameter of the connection flanges of 65 mm, a permanent flow rate of 65 m^3/h, and a metrological Class B.
- **WIW65M/WIW65:** This meter meets the ISO 4064-1:1993 specifications. The connection flanges have a nominal diameter of 65 mm and the permanent flow rate of the meter is 40 m^3/h. It has been classified as a Class B meter in all positions. However, the manufacturer recommends the installation of a flow stabilizer immediately upstream the meter.
- For this particular brand, two units had to be tested. The first one (WIW65M) showed an under-registration of approximately −16% throughout the measuring range. This unit was substituted by a new one (WIW65) which did perform according to specifications.
- **WSM65:** ISO 4064-1:2014 approval with a permanent flow of 50 m^3/h, a nominal diameter of the connection flanges of 65 mm and a flow profile sensitivity class of U3-D0.

2.3.3. Ultrasonic

Ultrasonic meters calculate the velocity of water from the speed of sound propagating in a moving medium [20,23]. Two sensors placed in the pipeline emit and receive ultrasonic waves simultaneously. When the flow is zero, the travelling time on both directions are equal. When water is moving, the sound waves move faster when travelling downstream than upstream. Flow velocity is obtained based on this time difference. The flow rate is obtained by multiplying the cross-sectional area and the velocity of water obtained by the meter. For these meters to work, the amount of suspended solids, impurities or air bubbles floating in the flow need to be small. Otherwise, the sound signal from one sensor will not reach the opposite sensor.

One brand of ultrasonic meter was tested.

- **UAO100:** ISO 4064-1:2014 approval with a permanent flow of 100 m^3/h, a nominal diameter of the connection flanges of 100 mm and a flow profile sensitivity class of U0-D0. This meter also follows AWWA C750 recommendation.

2.3.4. Electromagnetic

Electromagnetic meters are well-known for their high accuracy and reliability [20,23]. The working principle is based on the Faraday's law of electromagnetic induction. When an electromagnetic field is applied perpendicular to the flow, it induces an electrical voltage that is proportional to the average velocity of water through the section. By measuring the induced voltage and knowing the cross-sectional area, the flow rate through the meter can be easily calculated. Their measuring capabilities are independent of the physical properties of the fluid, such as viscosity, density or temperature and they are not intrusive, which means that there is no obstruction blocking the free passage of water.

Only one electromagnetic meter was tested in this study:

- **ESS100:** This meter was not approved following the ISO 4064 standard. For this reason, it cannot be assigned to a particular metrological class. However, according to the specifications of the manufacturer the accuracy of the meter is ±0.4% of rate ±2 mm/s for flow velocities between 0.1 m/s and 10 m/s. The nominal diameter of the connection flanges were 100 mm, and the length of straight pipe required upstream and downstream was 5D and 3D respectively.

2.4. Valves Used to Produce Flow Profile Distortions

Two different types of valves (Figure 3) were used to induce flow disturbances: a butterfly valve and a gate valve:

- **Butterfly Valve:** For each meter, accuracy tests were carried out for various upstream distances between the valve and the meter, orientation of the valve, defined by the orientation of the butterfly shaft, as depictured in Figure 4, and closing position. More precisely the following closure degrees were considered in the tests: 0%, 33%, 66% and 90%. Flow profile distortions have shown to cause dissimilar effects on the measuring errors of the meters depending on the closing position of the disc, the distance between the meter and the valve and the working principle of the meter.
- **Gate Valve:** The same criteria has been used as for butterfly valves. Water meters under examination have been tested with the valve installed at various distances from the water meter, with different degrees of closure and valve orientations. The closure percentages of the gate valve tested were 0%, 33%, 66/70% and 83/92%. This percentage is measured considering the total displacement of the gate from a fully open to a fully closed position.

Figure 3. Butterfly valve (**up**); gate valve (**down**).

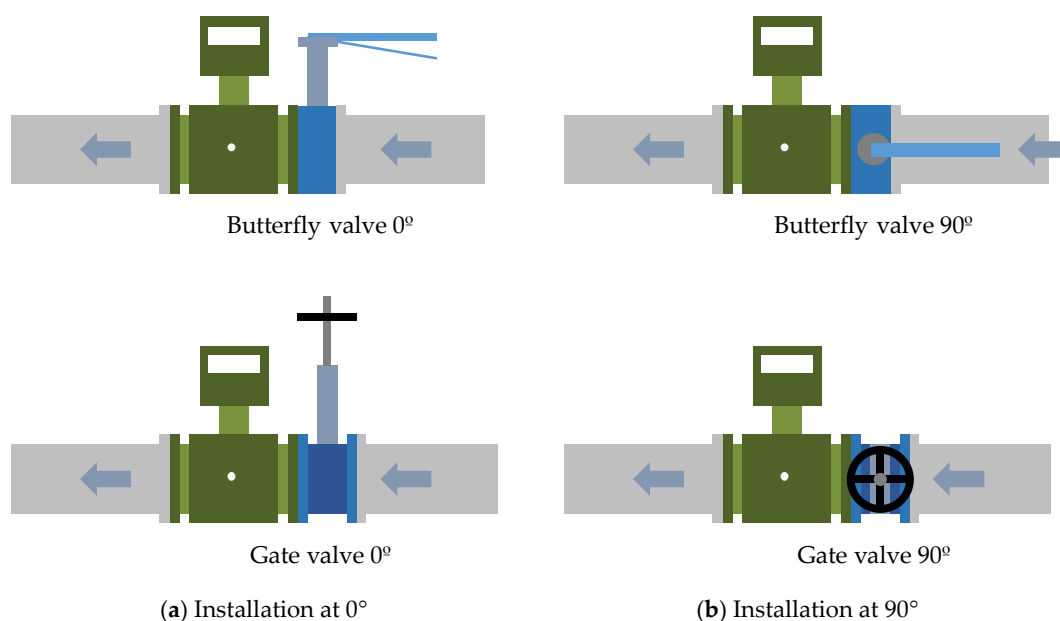(**a**) Installation at 0°   (**b**) Installation at 90°

Figure 4. Criteria followed to define the orientation of the valve.

2.5. Flow Rates Tested

For each water meter, the measuring error at five different flow rates was obtained. The selection of the flow rates to be tested took into account that the main purpose of the study was to obtain a better representation of the real metrological performance of the water meters in the field. Frequently water consumption flow rates and the normalize flow rates which characterize the metrological class of the meter do not match. Moreover, the minimum and transition flow rates of those water meters with the best metrological class are extremely close together in the lower side of the range, leaving a large portion of the range without any information on the measuring error. Therefore, the final selection of flow rates for each meter size (Table 3) was not based on these standardized values. Instead, it tried to cover as much as possible of the measuring range of the tested meters. In addition, by increasing the number of flow rates, it was possible to achieve some redundancy and identify potential incongruences in the results.

Table 3. Test flow rates by meter type.

Flow Rate Designation	Meter Type			
	CDA65/CES65/ CIF65	WDW65/WEH65/ WIW65/WSM65	ESS100	UAO100
Qa	0.15 m^3/h	0.70 m^3/h	4.70 m^3/h	0.37 m^3/h
Qb	0.30 m^3/h	3.10 m^3/h	12.5 m^3/h	0.70 m^3/h
Qc	13.3 m^3/h	14.7 m^3/h	39.0 m^3/h	33.0 m^3/h
Qd	27.0 m^3/h	30.0 m^3/h	80.0 m^3/h	67.0 m^3/h
Qe	50.0 m^3/h	50.0 m^3/h	100 m^3/h	120 m^3/h

2.6. Uncertainity of the Tests

Uncertainties have been calculated as follows: gravimetric tanks with EURAMET Calibration Guide No. 18 [34], density of water with ISO 4185:1980 [35], water temperature, air temperature and humidity, density of air and determination of volume with EURAMET Calibration Guide No. 19 [46], meter resolution with ISO 4064-1:2014 [40] and measurement process with ISO 5168:2005 [47].

The overall uncertainty of the tests, shown in Table 4, was obtained taking into account the reading resolution of the totalized volume of each meter and the characteristics of the testing equipment and

the reference tank used for each meter type and flow rate. The high uncertainty at low flow rates is due to the relationship between reading resolution of flow meters, as high as 1 L in case of WEH65, and the total volume of the gravimetric tank used for those flow rates (TNK3).

Table 4. Uncertainty for each meter and flow rate.

Flow Rate Designation	Meter Type						
	CES65 CIF65	CDA65	WEH65	WIW65	WSM65 WDW65	UAO100	ESS100
Qa	3.41%	1.37%	6.81%	1.4%	3.4%	0.3%	0.3%
Qb	3.41%	1.37%	0.62%	0.3%	0.3%	0.3%	0.3%
Qc	0.41%	0.3%	0.62%	0.3%	0.3%	0.3%	0.3%
Qd	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Qe	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%

2.7. Test Program Description

The purpose of the study was to establish the sensitivity of different types of large water meters to flow profile distortions caused by gate and butterfly valves installed upstream the meters. The effect of the valve on the measuring error of the meters was obtained at different flow rates throughout the measuring range considering the particular metrological class of the meter.

For the design of the test program, the main hypothesis used to conduct the tests was that the closer the valve was installed upstream the meter, the greater the magnitude of the disturbance reaching the meter and the effect on the error. Therefore, if a valve directly clamped to the meter does not cause a significant disturbance, it was expected that if a straight section of pipe was installed between the valve and the water meter, the new configuration would also have a negligible effect on the water meter error.

For this reason, the first test performed for each meter, valve, valve orientation and closure degree was conducted with the valve flanged directly to the meter. In this case the valve is defined as to be 0D upstream the meter. The results from this test are compared with the reference error curve of the meter, which is the one obtained under ideal test conditions, with more than 10 diameters of straight pipe upstream the meter. If there are no significant differences between both error curves the test for this specific valve, valve opening and valve orientation is terminated. The thresholds used to continue or terminate the tests are driven by the uncertainty associated to each test and the maximum allowable error change. As a general criterion, it is considered that there are no significant differences, and the test can be terminated, when the variation with respect to the reference error curve is within ±5% between Qa and Qb, interval with the greatest uncertainty, and within ±2% for the rest of the flow rates, coinciding in most cases with the limits of the class of the meter to which it belongs. Otherwise, a new test is performed with an additional straight pipe section of three diameters of length (3D) mounted between the meter and the valve. Then, the same criteria as before is used to continue or stop the test under the same working conditions. The length of the straight pipe sections considered are 0D, 3D, 5D and 10D, which means that the straight length of the pipe used can be obtained by multiplying the number before D and the nominal diameter, D, of the pipe. Straight distances longer than the later have not been considered and it has been assumed that for the meters under examination that distance is long enough to mitigate any effect of any flow disturbance. At this stage, it should be noted that most of the meters tested during the study had a classification for flow disturbance sensitivity of U0-D0 m. A summary of the tests conducted is presented in Table 5.

Table 5. Summary of the tests conducted.

Valve Type	Working Principle	Orientation	Closure	0D	3D	5D	10D
Gate	Single-jet	0°	0%	✓			
			33%	✓			
			66%	✗	✗	✗	✓
			83%	✗	✗	✗	✓
		90°	0%	✓			
			33%	✓			
			66%	✓			
			83%	✗	✗	✓	
	Woltmann	0°	0%	✓			
			33%	✓			
			66%	✗	✓		
			83%	✗	✓		
		90°	0%	✓			
			33%	✓			
			66%	✓			
			83%	✗	✗	✓	
	Ultrasonic	0°	0%	✓			
			70%	✓			
			90%	✗	✓		
		90°	0%	✓			
			70%	✓			
			90%	✗	✓		
	Electromagnetic	0°	0%	✓			
			70%	✗	✗	✗	
			90%	✗	✗	✗	✓
		90°	0%	✓			
			70%	✗	✓		
			90%	✗	✗		✓
Butterfly	Single-jet	0°	0%	✓			
			33%	✓			
			66%	✗	✗	✗	✓
			83%	✗	✓		
		90°	0%	✓			
			83%	✗	✗	✗	✓
	Woltmann	0°	0%	✗	✗	✗	✓
			33%	✗	✗	✗	✓
			66%	✗	✗	✗	✓
			83%	✗	✓		
		90°	0%	✓			
			33%	✗	✗	✗	✓
			66%	✗	✗	✗	✓
			83%	✓			
	Ultrasonic	0°	50%		✓		
			70%	✗	✗		
			90%	✗	✗	✓	
		90°	50%		✓		
			70%	✗	✓		
			90%		✗	✓	
	Electromagnetic	0	0%	✓			
			50%	✗	✗	✓	
			70%	✗	✗	✓	
			90%	✗	✗	✓	
		90°	50%	✗	✓		
			70%	✗	✓		
			90%	✗	✓		

✗ Flow disturbance affects the accuracy. ✓ Flow disturbance does not affect the accuracy.

3. Results

Measuring errors at five different flow rates of the various metering technologies under study have been obtained in the laboratory. In order to standardize the results, and to facilitate their interpretation, characteristic test flow rates have been selected for each nominal diameter of the meters (Table 6). Furthermore, taking into account the substantial differences in behaviour found between different disturbances and meter technologies, results can only be analysed in qualitative and not quantitative terms. Because of this, the charts presented in this manuscript show the error distribution at the five different flow rate tested by means of box-whisker plots. In these charts the interquartile interval, mean, median and extreme values can be easily identified, so they are an excellent tool to compare general behaviours of the meters and to show the qualitative effect of a specific flow disturbance.

Table 6. Reference error in percentage of the meters under calibration.

Flow Rate Designation	Meter Type								
	CES65	CDA65	CIF65	WEH65	WIW65	WSM65	WDW65	UAO100	ESS100
Qa	0.42	−1.35	1.23	0.25	−1.47	0.14	−3.18	−7.27	0.64
Qb	0.71	2.34	0.66	0.82	−1.75	0.38	−2.33	−4.05	0.29
Qc	−1.26	1.99	1.16	−0.76	−1.30	−0.58	−1.14	−1.18	−0.52
Qd	−1.02	1.89	0.92	−1.14	−1.34	−0.36	−1.2	−0.51	−0.03
Qe	−1.02	2.12	0.75	−2.01	−1.47	−0.12	−1.07	−1.04	0.09

3.1. Reference Error of the Meters under Examination

Table 6 shows the individual reference error curve, when no distortion is introduced in the flow, of all meters tested. These results are included for comparison purposes in a consolidated box-whisker plot in every figure. This data series has been named as "Error (%)" and plotted in red colour.

3.2. General Overview of the Effect on the Measuring Errors of a Gate and Butterfly Valve

With the purpose of facilitating the interpretation of the findings and considering the number of potential combinations between variables under analysis and the huge variability of the results, measuring errors of the meters have been grouped by flow rate in box-whisker plots defined by the variable under examination. The idea is to present in a single graph the overall variability of the measurement errors and the potential bias that can appear under specific working conditions. As detailed in the following sections, the effect of an upstream distortion on the metrological performance of a meter does not depended exclusively on its technology or the upstream valve type, design and closing degree or even how close the distorting element is upstream the meter. Various meters from a particular technology may show completely different behaviors under the influence of the same flow profile distortion. In other words, it is not possible to rise a general conclusion that can be applied to any meter type. For this reason, the main intention of the study was to provide an order of magnitude of the potential effect (measured as a function of the error change in comparison with the reference errors) of a distortion introduced upstream by a gate or a butterfly valve.

Figure 5 summarizes the errors found at five different flow rates of all meters tested grouped by type of valve. Although the gate valve used caused significant measuring errors in specific types of meters (see Figure 5), in general terms, variability and magnitude of the errors, as shown by the size of the interquartile range and data point dispersion, is comparatively larger when the distortion is caused by a butterfly valve. Flow distortions caused by a butterfly valve can lead to extreme measuring errors. For example, a butterfly valve with a 90% closing degree installed 0D upstream of an ultrasonic meter showed errors of 293% (Qa), 768% (Qb) and 197% (Qc) (note that these data points are out of the scale range of the plot presented in Figure 5). The random behaviour at Qb demonstrates the difficulty of predicting the performance of a meter under a flow profile distortion.
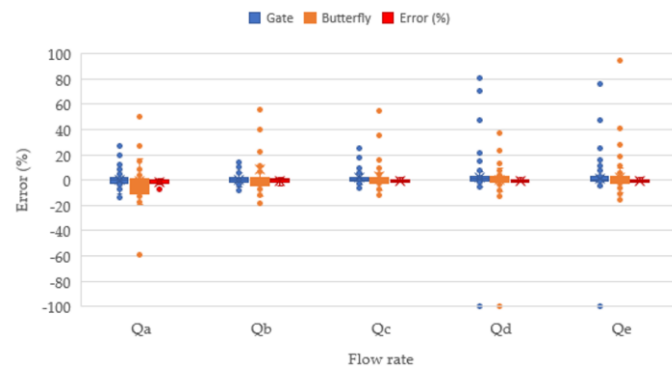
Figure 5. Butterfly and gate valves. Overall view.

3.3. Measuring Errors Caused by a Butterfly Valve

This section details the performance found for the different types of water meters when a butterfly valve, like the one presented in Figure 3, is installed upstream. Various settings of the butterfly valve have been examined considering the following variables: upstream distance to the tested meter, orientation of the valve, closing degree and flow rate. Figure 6 shows that, in general terms, the dispersion of measuring errors is significantly larger in comparison to the reference performance in which the flow profile distribution reaches the water meter fully developed, without any distortion.
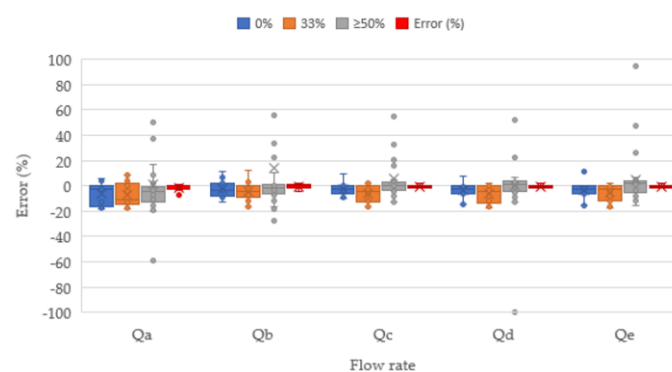
Figure 6. Butterfly valve, closing percentage.

In addition, from the same figure, it is no possible to sustain that the presence of the butterfly valve can consistently cause under or over-registration of the meters.

3.3.1. Closing Percentage of the Valve

The first variable to be examined is the effect of the closing degree of the valve. For simplification purposes, the results for closing degrees greater or equal than 50% have been grouped together. Figure 6, shows the results obtained for all meters at different flow rates and closing degrees. As expected, the larger influence of the valve on the errors is caused for closing degrees greater than 50%. Figure 6 also shows that the larger the closing degree the greater the dispersion of the measuring errors of the meters. From a revenue perspective, even though closing degrees of 50% or larger can lead to negative errors (in one case an ultrasonic meter completely stopped), there are more chances to get positive errors. In fact, the influence of a butterfly valve installed upstream caused that in 20 tests the original error increased to a figure larger than 20%, and only in 6 tests the error decreased below −20%.

It is also important to highlight the fact that even with a fully open valve the dispersion of the errors is considerably larger than the dispersion obtained for reference conditions. This means that for specific meter types and settings, having a fully open valve upstream does not guarantee that the distortion caused by the valve will not have a significant effect on the error.

Figure 6 clearly shows that measuring greater than ±20% were only caused by closing degrees of the valve larger than 50% independently of how close the valve was located upstream the meter. The sign of the errors found is not always in one way. However, it has been found that for his closing degree, on average, there is a slight tendency to over registering water. With a 33% closing, most of the errors obtained were negative, which means that there is a high probability of under registering water consumption. Finally, for 0% closing, the errors found are significantly smaller than for other closing degrees. Only at low flows, Qa, a noticeable under registrations of the meters, when compared to the reference errors, have been found.

For the particular case of the meter UAO100, at a flow rate of Qd and a 70% closing degree, a measuring error of −100% was found. This means that the meter under these specific conditions was completely stopped. A similar result was expected at a larger flow rate of Qe. However, it was not possible to reach that flow rate because of the limitations of the test bench. This behaviour is typical of ultrasonic meters, which usually cut-off the flow signal when the velocity of water exceeds certain threshold.

3.3.2. Valve Orientation

The valve orientation can have an impact on the measuring errors of the meters. The difference is that, since 0° has less results out of the reference limits, they have a big differential, up to ±100%, while 90° has more points out of the limits but only between +40% and −15% approximately (Figure 7).
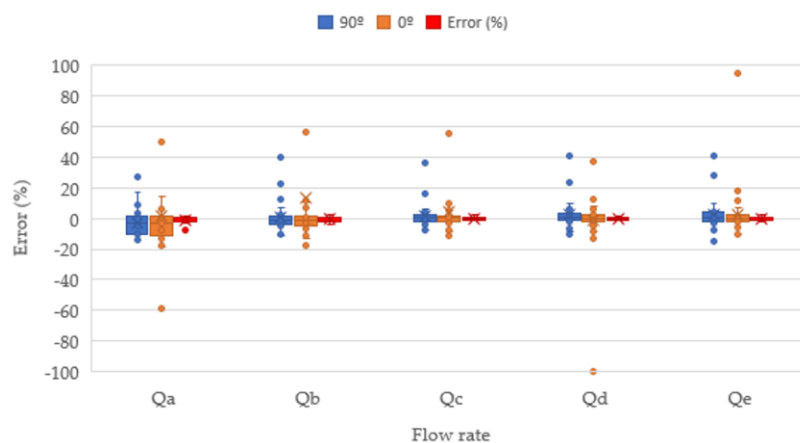
Figure 7. Butterfly valve 0° and 90° arrangement.

3.3.3. Upstream Straight Sections of Pipe

Figure 8, presents a summary of the results of the tests on all water meters with different upstream lengths of straight pipe. As expected, as the length of straight pipe between the disturbance and the meter is increased, the error dispersion decreases as recorded in Table 7.
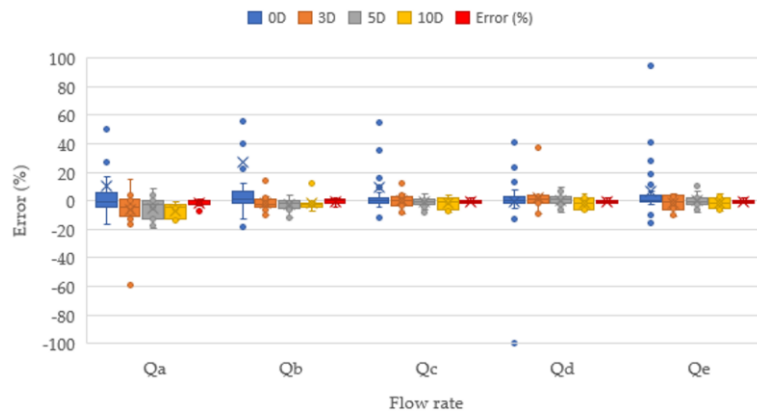
Figure 8. Diameters of straight pipe upstream.

Table 7. Maximum errors in percentage for different straight pipe sections.

Straight Pipe Sections	Maximum Errors (%)	Std. Deviation (%)
0D	+100/−100	65.8
3D	+35/−15	7.9
5D	+10/−18	7
10D	+10/−15	6.4

3.3.4. Technology of the Water Meter

There are large differences in behaviour for the different technologies (Figure 9). Single-jet, meters produce both under and over-registration, without large deviations with respect the reference conditions. The more positive and negative errors found were −18% and +8% respectively. Woltmann technology is undoubtedly the one that it is most affected by the presence of a butterfly valve. Depending on the closing degree of the valve and distance from the meter, huge over registrations, up to +100%, have been found. Ultrasonic meter is affected in an erratic manner; it is not greatly affected, similar to single-jet meters, until a certain flow is reached when it becomes "blind" and stops counting. Also, under extreme flow distortions it can present anomalous behaviours. For example, with the valve installed at 0D and 90% closing, the errors found were 293% for Qa, 768% for Qb and 197% for Qc. Electromagnetic meter is the technology that is least affected by the disturbance caused by a butterfly valve. The error under all the conditions tested fluctuated between ±10%.
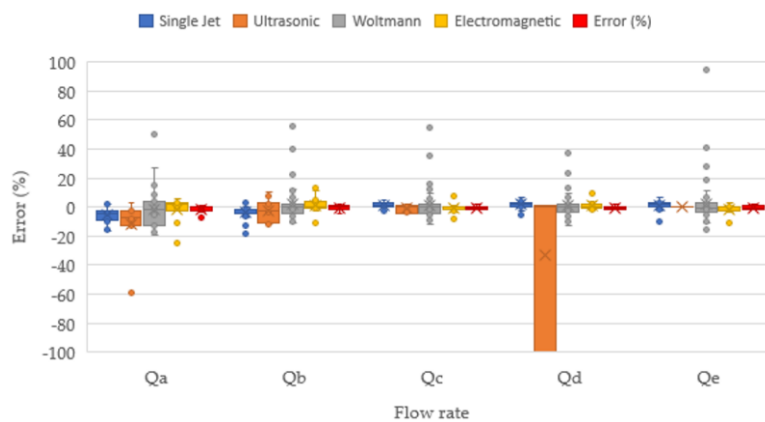
Figure 9. Different technologies of water meters.

3.3.5. Individual Test Results

The following section conducts an individual analysis of the meters under the presence of a butterfly valve. The error curve of the meter CDA65 is not particularly affected by the distortion of a butterfly valve. The variability of the error curve in the presence of such valve is within the admissible limits. Both, CES65 and CIF65 show a similar behaviour, under registering at low flows and presenting a slight over registration in the upper zone of the range. Meters WEH65, WIW65 and WSW65 tend to over register when the valve is installed at a distance of 0D and the closing degree is above 50%; this situation improves markedly when the length of straight sections of pipe upstream increases. From these meters, the one which is least affected is the WSW65, for which the maximum over registration does not exceed 15%. On the other hand, the meter that suffers the most the presence of the butterfly valve is WIW65 for which errors up to +70% have been found. WDW65 shows a low over registration and, unlike the rest of the meters with the same technology, a slight under registrations have been found. The most significant about UAO100, in addition to the large variability of results, which makes the behaviour of this meter unpredictable, is that from a certain flow rate with the valve at 0D and a closing degree greater than 70%, it stops counting and show an erratic behaviour. With the ESS100 m, under and over registrations have been detected. However, the magnitude of the errors have always been smaller than ±15% (Figure 10).
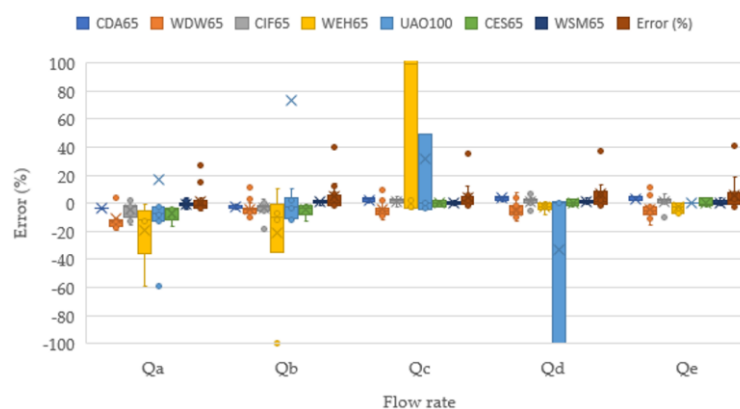

Figure 10. Individual test results for each flow meter.

3.4. Measuring Errors Caused by a Gate Valve

The work conducted also examined the influence of a gate valve installed upstream the meters under study. As shown in Figure 5, which summarizes the results of the tests conducted, gate valves may induce a severe effect on the accuracy of water meters, especially at large flows, producing a significant over registration of water volumes. Despite the fact that some negative errors have also been observed under the presence of a gate valve, the negative errors obtained were of an order of magnitude smaller when compared to the positive ones. This can be easily confirmed by the median an average value of the error distribution in Figure 5.

3.4.1. Closing Percentage of the Valve

As expected, the closing degree of the valve together with the upstream distance to the meter is one of the parameters that most affect the measuring accuracy. For closing degrees larger than 50% the errors tend to be positive and can easily reach figures larger than +30% (Figure 11). However, the effect on the error of a fully open gate valve, no matter the working principle of the meter and the upstream distance of straight pipe between the valve and the meter, is almost negligible (when compared in the same order of magnitude of the errors found when the valve is more than 50% open). This also seems to be the general behaviour when the gate valve is 33% closed. Errors become slightly

larger in comparison when the valve is fully opened but, rarely reached extreme values either positive or negative.
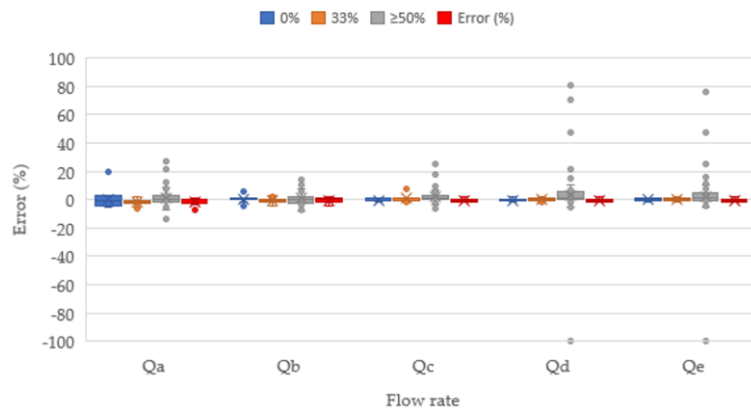

Figure 11. Gate valve, closing percentage.

3.4.2. Test Arrangements 90° and 0°

Unlike with butterfly valve (Figure 7), there are no significant differences on the effect of the disturbance between 90° and 0° arrangements of the valve, as shown in Figure 12. The median of the error distribution under both arrangements is close to cero, meaning that positive and negative error are equally probable to occur. However, it has been detected a larger proportion of tests showing errors of more than 30% when the gate valve is in 90° position. These are mainly originated in Woltmann meters due to the location of the adjustment device, which consists of a small paddle that locally changes the direction of flow modifying the incidence angle of water on the helix blade.
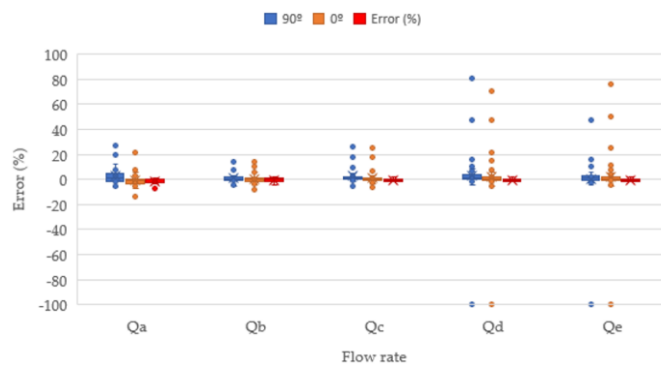
Figure 12. 90° and 0° arrangement.

3.4.3. Upstream Straight Sections of Pipe

Upstream straight pipe rapidly reduces the influence of the distortion caused by the gate valve at any flow rate (Figure 13). However, this figure also indicates that having a partially closed gate at 10D distance can significantly affect some meter types (Woltmann type) depending on their construction. In the particular case of the Woltmann meters tested, only one brand was affected by the presence of the gate valve 10D upstream. However, the closing degree in all cases was larger than 50%.

For all other technologies, as presented in Section 3.5, the effect of the flow distortion caused by the gate valve rapidly diminishes.
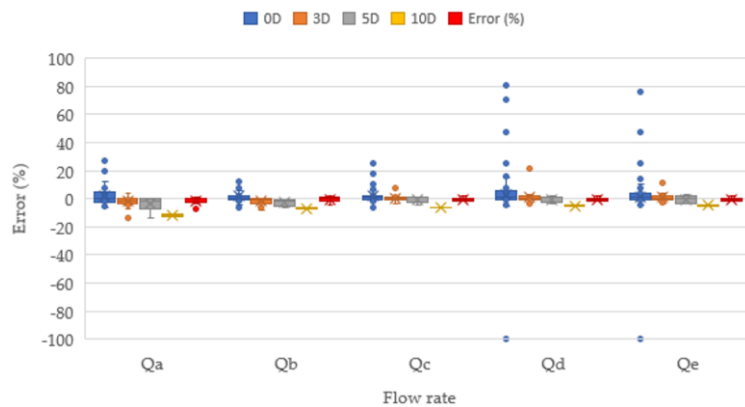
Figure 13. Diameters of straight pipe upstream.

3.4.4. Technology of the Water Meter

Water meter technology has demonstrated to be a major factor when analysing the effect on accuracy of upstream valves. However, meter construction and design also play a definitive role in the actual performance of the meters under the influence of a flow distortion. For this reason, two different meter brands of a given technology may exhibit dissimilar behaviours. Therefore, conclusions on the effect of a specific flow distortion cannot be generalised to other brands of meters of the same technology.

Analysing the tests conducted, single-jet water meters tended to over-register water consumption at medium and high flow rates, up to a maximum of 12%. Woltmann meters suffered from both, over and under-registration, of water consumption. However, the magnitude of the over-registration errors found was larger, especially at high flow rates. Some tests, with the gate valve installed just upstream the meter and a closing degree greater than 50%, led to measuring errors of +50% or more. Ultrasonic meters presented a behaviour similar to the one found under the presence of a butterfly valve. These meters stopped recording at flow rates above a certain threshold (below the overload flow), when the gate valve closing degree was significant. The errors obtained for the electromagnetic meter under study were positive and negative. However, as shown in Figure 14, negative under-registration errors seemed to prevail over positive errors.
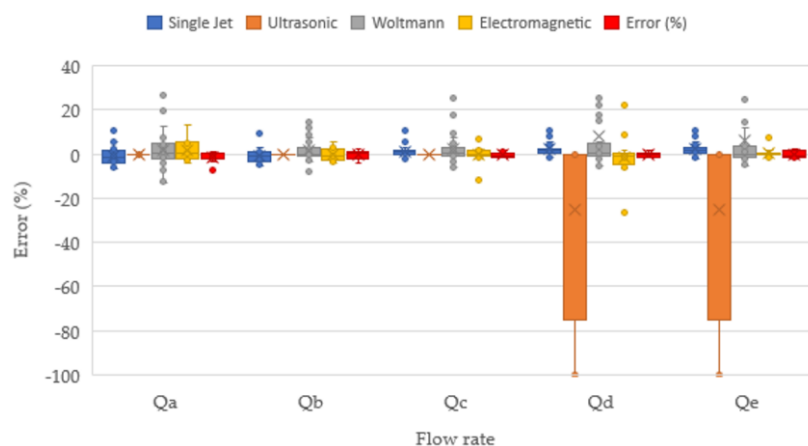

Figure 14. Different technologies of water meters.

3.4.5. Individual Test Results

Figure 15 depictures the error distribution of the various brands of meters examined in this wok. The typical interquartile range magnitude is in most cases between 10–15%. Only few of the meters

tested showed a narrow interquartile range. Examples of this performance are the meters marked as CIF65, single-jet, and UAO100, ultrasonic.
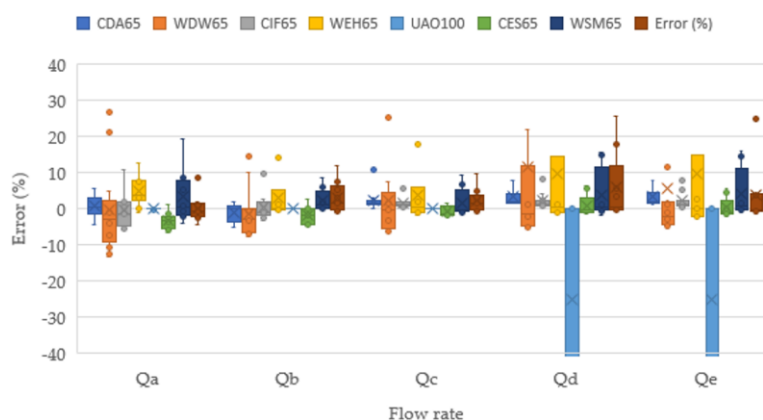

Figure 15. Individual test results for each flow meter.

The most remarkable characteristic of the meter identified as CDA65 is the over-registration, greater than 10%, that occurs at high flow rates when the valve is nearly completely closed and installed just upstream the meter. WDW65 shows some under-registration and a very high over-registration exceeding 80% at high flow rates. CES65 displays over-registration over 6% at high flow rates, while maintaining the accuracy at medium and low flow rates. On the other extreme, WEH65, exhibited a significant over-registration, greater than 50%, especially at high flow rates and when the closing degree of the gate valve is 50% or more.

3.5. Summary

The main conclusions are summarized below in Tables 8 and 9. For easiness of interpretation, tests results are simplified, and the tables do not provide the exact details of the errors obtained at each flow rate. Consequently, they only give an estimate of the influence on the original error of the various disturbances examined for each meter technology. These tables have been prepared with the purpose to serve as a rough indication of how much the error of a meter of a given technology could deviate from the performance under an undistorted flow. Obviously, as described in the previous sections, the actual influence of the perturbance could significant vary depending on the flow, design of the meter and severity of the disturbance. For this reason, the figures provided in Tables 8 and 9 should only be taken as a qualitative measure.

The following considerations should be made for properly interpreting the tables:

- Blank spaces indicate that there is no influence expected from a distortion located at that distance from the meter. The checkmark also indicates that, from the tests conducted, a distortion located at that specific distance from the meter did not have any significant effect in the measuring errors of the meters.
- The errors shown in the tables are typically the extreme errors that can be expected according to the results obtained from the tests.

Table 8. Butterfly valve placed upstream different water meter technologies.

BUTTERFLY VALVE							
Technology	Position	Config.	Closing (%)	0D	3D	5D	10D
Single-Jet	Upstream	0°	66	+6%	+4%	+4%	✓
		90°	66	+6%	+4%	✓	
Woltmann	Upstream	0°	66	+60%	+60%	+6%	±5%
		90°	66	+40%	+40%	+10%	±5%
Ultrasonic	Upstream	0°	70	−100%	✓		
			90		−60%	−15%	✓
		90°	70	−100%	−8%		✓
			90			−6%	✓
Electromagnetic	Upstream	0°	70	+10%	✓		
		90°	70	+12%	✓		

✓ Flow disturbance does not affect the accuracy.

Table 9. Gate valve placed upstream different water meter technologies.

GATE VALVE						
Technology	Position	Config.	Closing (%)	0D	3D	5D
Single-Jet	Upstream	0°	83	±15%	+4%	✓
		90°	83	±15%	+4%	✓
Woltmann	Upstream	0°	66	±7%	✓	
			83	+80%	✓	
		90°	66	±5%	✓	
			83	+80%	✓	
Ultrasonic	Upstream	0°	90	−100%	✓	
		90°	90	−100%	✓	
Electromagnetic	Upstream	0°	90	+7%	+7%	✓
		90°	90	−25%	−5%	✓

✓ Flow disturbance does not affect the accuracy.

4. Conclusions

According to the results of the tests conducted and taking into consideration the previous hypotheses, the following conclusions may be raised:

- Gate and butterfly valves may produce a great distortion on the error curve of a water meter when installed immediately upstream of the meter.
- Measuring errors increase with the closing degree of the valves. Closing degrees of less than 33% do not cause significant measuring errors when compared with those produce for larger closing degrees.
- For the nominal diameters tested, between 65 and 100 mm, the length of straight pipe upstream of the meters has also proved to play a major role in mitigating the influence of a flow disturbance caused by a gate or a butterfly valve. The length of straight pipe sections needed to eliminate the influence on the error curve of the perturbance also depends on the technology of the meter.
- As expected, not all measuring technologies are equally sensitive to flow disturbances. However, even for the same technology, variations in design, negligible a-priori, can significantly affect the error of a meter subject to an upstream flow distortion.
- The performance of the meters under study, installed downstream the two types of valve considered, turned out to be very similar. Both valves, each one with its particularities, can produce large measuring errors.
- By technology, it can be highlighted that single-jet and ultrasonic meters were the most unsensitive to the flow disturbances originated by the upstream valves. However, the ultrasonic meters tested, under certain flow conditions within the measuring range, completely stopped registering water

flows. It is recommended to examine in more detail the reasons of this performance so the real impact in the field can be established.

- Even though most of these meters are classified as U0 according to ISO 4064-1:2018, several of them were affected by flow distortions produced by valves installed upstream. This is an important consideration when installing water meters classified as U0. This classification does not necessarily imply that the water meter is completely insensitive to any type of flow disturbance upstream the meter.

Based on the results obtained, inspecting the installation conditions of medium and large water meters can be very valuable for both, the customer and the water utility. Measuring errors can indistinctively be positive or negative and, therefore, both parties may be economically affected by an incorrect installation of the water meter. In the particular case of the customer, the invoice can grow up to twice the actual consumption, as in some known cases that have been reported. This can even be worse considering the tariff structure of the water utility. On the utility side, as reported by the results in this study, under specific circumstances the under-registration of the meter can be considerable. In particular, the ultrasonic meter tested, when installed downstream of a partially closed valve (more than 66% closed) and high flows stopped counting.

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