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Inovações e Soluções Sustentáveis em Engenharia Ambiental

Can venturi flowmeters be used to measure residential consumption?

Os medidores de vazão venturi podem ser usados para medir o consumo residencial?

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ABSTRACT

Flow measurement is critical for the management of processes involving fluids. Depending on their location, meters can be classified as macro flow meters or customer flowmeters. Accounting for water inflows and outflows is essential to manage revenues and losses and can be measured through different instruments with different principles of application. A few research related water losses and the use of macro flowmeters in the water distribution networks (WDN) regarding its precisions and costs. For residential consumption registration, volumetric and velocimetric meters are often the most used type of meter as it presents a good cost/efficiency relation. In this sense, the main objective of this research was to compare the simple Venturi meter with the most used residential flowmeters: velocimetric, volumetric and ultrasonic meter. Experimental studies were carried out on a 20 mm diameter calibration bench by volumetric method, in the calibration facilities laboratory. Experimental results are presented and analyzed. Results shows that by applying a discharge coefficient based on experimental adjusted equations Venturi meters can perform similarly to the other meters studied.

Keywords: Consumer water meter; Venturi meter; Hydrometer

RESUMO

A medição de vazão é fundamental para o gerenciamento de processos que envolvem fluidos. Dependendo de sua localização, os medidores podem ser classificados como macromedidores de vazão ou medidores de vazão do cliente. A contabilização das entradas e saídas de água é essencial para gerenciar receitas e perdas e pode ser medida por meio de diferentes instrumentos com diferentes princípios de aplicação. Algumas pesquisas relacionaram as perdas de água e o uso de medidores de vazão nas redes de distribuição de água (WDN) em relação a suas precisões e custos. Para o registro do consumo residencial, os medidores volumétricos e velocimétricos costumam ser os mais utilizados por apresentarem uma boa relação custo/eficiência. Nesse sentido, o principal objetivo desta pesquisa foi comparar o medidor Venturi simples com os medidores de vazão residenciais mais utilizados: velocimétrico, volumétrico e ultrassônico. Os estudos experimentais foram realizados em uma bancada de calibração de 20 mm de diâmetro pelo método volumétrico, no laboratório de instalações de calibração. Os resultados experimentais são apresentados e analisados. Os resultados mostram que, ao aplicar um coeficiente de descarga (Cdex) com base em equações ajustadas experimentalmente, os medidores Venturi podem ter desempenho semelhante ao dos outros medidores estudados.

Palavras-chave: Medidor de água para consumo; Medidor Venturi; Hidrômetro

1 INTRODUCTION

According to Tomaszewski, A. et al. (2020), accurate flow measurement is important in several applications. There is a wide variety of devices for flow measurement, and it should be chosen according to the application, particularities of the flow and characteristics of the meter such as uncertainty, costs, lifetime, ease of installation and feasibility of performing the calibration. A fluid flow meter is defined as an instrument designed to measure continuously, record information and instantly display the measured values of the volume of water passing through the measuring device (ISO 4064-2: 2017).

There are different ways to classify flowmeters, but often they are classified according to the operating mechanism as mechanical meter, differential, ultrasonic and electromagnetic (Coelho 1983). Mechanical meters are the most used for registering residential consumption and they can be sub-classified as volumetric or velocimetric meters. Each type of meter, with its unique characteristics, are considered suitable for different applications.

For instance, velocimetric meters measure flows based on the velocity of a rotating propeller; because of its simple mechanism, it has a low cost and easy maintenance, however it is less precise (Neto et al. 1998). On the other hand, volumetric meters measure flows by counting how many times a small container with known volume is filled. They have better precision when compared to velocimetric meters but have higher cost and are sensitive to suspend solids that can block the passage (Tsutiya 2006).

Electromagnetic meters create a magnetic field perpendicular to the flow, in a way that the magnetic field can be determined based on the force produced by the flow movement. Although more expensive than mechanical meters, they offer greater accuracy, negligible losses, compatibility with any pipe diameter, and no moving parts (Martim 2005). According to ISO 12242: 2012, Ultrasonic meters are equipped with sensors that send and receive ultrasonic waves after they have propagated through the fluid. Among the many ultrasound measurement techniques, Doppler effect and the transit time are the most widespread. According to Joshi (2021), ultrasonic flowmeters have a wider dynamic range, greater accuracy, better reliability, require less maintenance and contain no moving parts; however, they cost more.

Differential pressure meters measure flow based on the difference of pressure between two points. According to (Kambayashi, Izuru; Kang, Donghyuk; Nishimura 2020), differential pressure flowmeters can measure flow rates regardless of fluid type and non-specific velocity profile. Graham (2020) points out that Venturi meters are among the most common types of devices used worldwide for flow measurement, as they are simple, robust, reliable, and cost effective. They are mostly used as macrometers.

The Venturi tube device consists of a converging cone-shaped inlet tube section (the converging section) connected immediately before a cylindrical throat which, in turn, is connected in front of a cylindrical cone-shaped expansion tube (the diverging section). The pressure difference between the sections of the Venturi tube is proportional to the flow velocity and, in this way, it is possible to indicate the instantaneous flow rate in the tube, provided that it is completely filled with water (ISO 5167-1: 2022). There are three classical geometries for the Venturi meter, and the discharge coefficient can be selected respectively. Whenever the device geometrically resembles one that has been calibrated under the same conditions, the flow rate can be determined in accordance with ISO 5167-1:2022. Also according to the ISO standard, classic Venturi tubes cover a diameter range from 50 mm to 250 mm. And the ratio between the internal diameters, called β, can vary from 0.4 to 0.75. For installations outside these limits, it is necessary to calibrate the meter in the installation situation.

The main objective of this research was to compare the simple Venturi meter with the most used residential flowmeters: velocimetric, volumetric and ultrasonic meters. Experimental studies were conducted in the calibration facilities laboratory using a 20 mm diameter calibration bench and the volumetric method.

2 VENTURI FLOWMETERS

According to Varin (2019), Venturi tubes were designed according to the French and European standard ISO 5167-4: (2022), although this standard was not strictly applicable to the Reynolds number ranges. This design method can allow high-precision measurements if the flow coefficient considers fluid compressibility and pressure losses in the Venturi tube. The mass flow rate in a Venturi tube is derived from the Bernoulli equation. These devices follow the laws of Bernoulli and continuity and can be used to estimate the mass flow rate, as long as the dimensions of the flow and installations are known. In addition, the most important parameter is the β ratio. However, as in practice flows are not always laminar, compressible, and frictionless flow is not a reality, some corrections must be made. To determine the mass flow rate of the fluid we must use Equation [1] (ISO 5167-1:2022) with the flow parameter (Tomaszewski, Adam; Przybylinski, Tomasz; Lackowski 2020).

$$Qm = \frac{Cd}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{2 \cdot \rho_1 \cdot \Delta_P} \tag{1}$$

where:

Qm is flow mass [kg/s];

 is discharge coefficient for Venturi meter and assumed standard value is 0.9792, to β equal to 0.47;

d is throat's diameter of the venturi meter [m];

Δ_p is the static pressure difference [mH_2O].

β is the diameter ratio of the diameter of the throat (d) of the primary device to the internal diameter of the measuring pipe upstream of the primary device (D).

ε is the expansibility [expansion] factor, a coefficient used to consider the fluid compressibility, which is equal to one unit when the fluid is considered incompressible (liquid).

ρ is the density of the fluid [kg/m^3].

In relation to a given fluid that passes through the Venturi tube, the radial and circumferential pressure gradients are negligible, that is, even with an increase in pressure, its volume does not decrease, and its density does not increase considerably. For practical applications, it is common to assume that the fluid is incompressible. (Kambayashi, Izuru; Kang, Donghyuk; Nishimura 2020).

The performance of the venturi flow meter is evaluated at constant flow rates to establish the discharge coefficient based on the Reynolds number in the throat section. The final discharge coefficient adjusts the measured flow rate considering all pressure losses due to friction along the walls. In the contraction section, the static pressure of the fluid is converted into velocity, and the static pressure drops. On the other hand, in the diffusion section, the velocity of the fluid is converted back into static pressure, and the static pressure increases (Zhang 2019, and Beauleu et al. 2011).

By calculating the constants of the Equation [3], and considering that the fluid is incompressible (that is $\rho 1$ is equal to $\rho 2$)) and that the volumetric flow rate is obtained by dividing the mass flow rate by ρ, we arrive at the simplified Venturi equation, shown in Equation [2], as presented by Delmée (2003).

$$Q = 1.1107 \cdot Cd \cdot E \cdot \beta^2 \cdot D^2 \cdot \sqrt{\left(\frac{P_1 - P_2}{\rho}\right)} \tag{2}$$

where:

E is the correction factor given by Equation (3):

$$E = \frac{1}{\sqrt{1-\beta^4}} \quad (3)$$

D is the diameter of the Venturi tube at section 1 (in meters)

$P1$ and $P2$ are the pressure readings taken at sections 1 and 2 of the Venturi tube, respectively, where section 2 corresponds to the throat of the meter

3 METHODOLOGY

In this work, a Venturi-type flow meter was studied and tested alongside other meters with different operating principles, in order to provide a comparative evaluation and suggest an operational strategy to take advantage of the Venturi meter. A 20 mm diameter pipeline test bench, operating on the volumetric principle, was used for all tests conducted in this work, based on ISO 8316:1987. And based on the comparative results, an adjustment to the Venturi equation was suggested to improve the results and reduce the error of deviation in the indication of flow rates. The discharge coefficient is an important parameter for determining the flow using a Venturi meter. However, this coefficient is often not calculated but rather obtained through adjustment. Therefore, for the purposes of this research, the coefficient (Cd_{ex}) will be calibrated and determined experimentally.

The tests with the flow meters were performed on a hydrometer bench test, with all meters installed in the same pipeline for each test. Figure 1(a) shows the bench test in operation. The bench has two lines, allowing simultaneous operation. In this study, the calibration line on the right side, shown in Figure 1(b), was used.

The workbench operates on the principle of volumetric calibration, as described in ISO 8316:1987. In this system, a closed-loop line is fed by a lower reservoir, and all flow passing through the flow meters is collected in a stainless steel standard tank of known volume. To minimize the effects of volumetric variation, the room temperature was controlled and kept constant. The volume variation of the standard tank as a function of temperature variation is of the order of 0.07%.

The standardized volumetric tanks have three compartments. The first, for the lower rate flow (from 2.5 to 10L/h) has a total volume of 2 litres. The second has a volume of 5 litres (from 22.5 to 40 L/h), and the third tank with 10 litres (from 100 to 1000 L/h) (Figure 1).

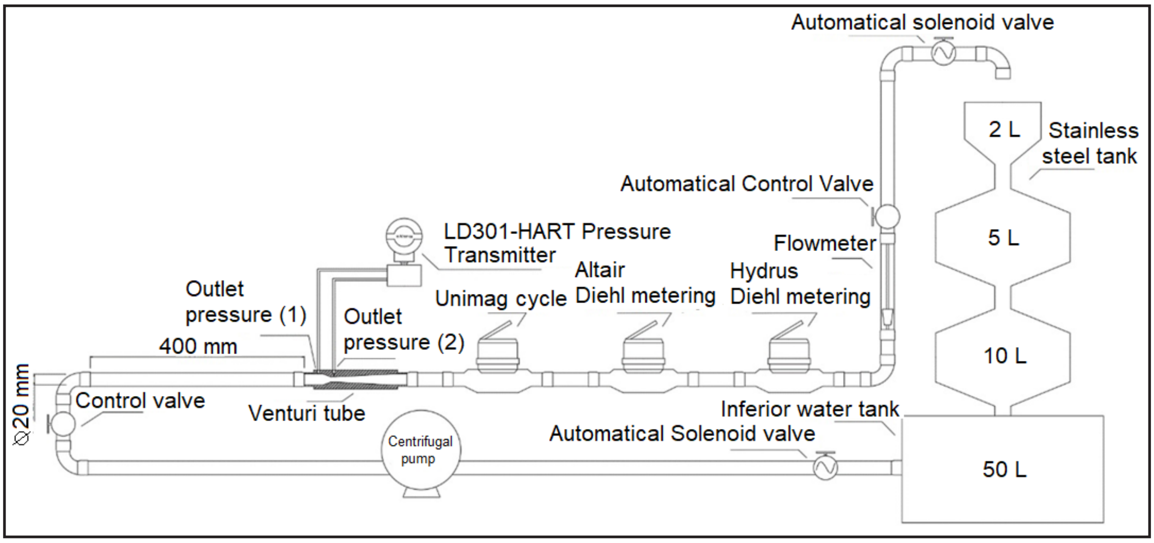
Figure 1 – (a) Bench test - Volumetric Principal ISO 8316:1987 (b) Flow meters evaluated installed in series

Source: the authors (2025)

The System is fully automated, with electrodes to stop the pump and closing valves when the water level reaches the maximum level at the tank. Therefore, flow control valves are automatically closed interrupting flow through the meters. The final volume drained and the duration of the test is reported on the control panel of the bench.

The initial reading of the meters (Velocimetric, Volumetric, and Ultrasonic) was recorded at the beginning of the test and at the end of each test. The totalized volume was obtained by the offset, using one of the volumetric tanks on the bench, as shown on Figure 2.

Figure 2 – Test Bench - Sanasa Lab



Source: the authors (2025)

With the values obtained from the test, the average flow rate was calculated using Equation [4] and recorded.

$$Q_{average} = \frac{d\forall}{dt} \quad (4)$$

where,

$d\forall t$= test volume;

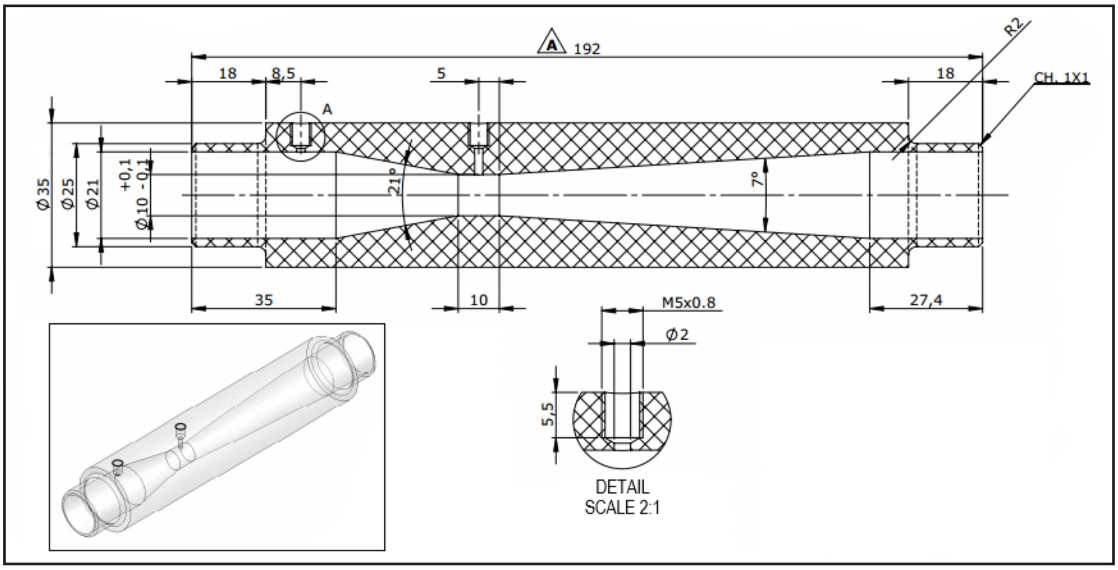
dt = test time and

$Q_{average}$ = average flow

The Volumetric and Velocimetric flowmeters display only the total water volume, without instantaneous flow information. The Ultrasonic flowmeter has a display that reports both the total volume and instantaneous flow information. The Venturi meter only has an instantaneous flow display in the differential pressure reading module (TP-301). Although it allows total volume programming, it was not used to allow calibration adjustments. Thus, the values of mean flow and total volume in time were calculated from the Venturi tube equation using a spreadsheet.

The Venturi tube used was built by the Labtrix company and has an internal diameter of 21 mm and a minimum section diameter of 10 mm. The other dimensions are shown in Figure 3.

Figure 3 – Dimensions of the Venturi Tube used



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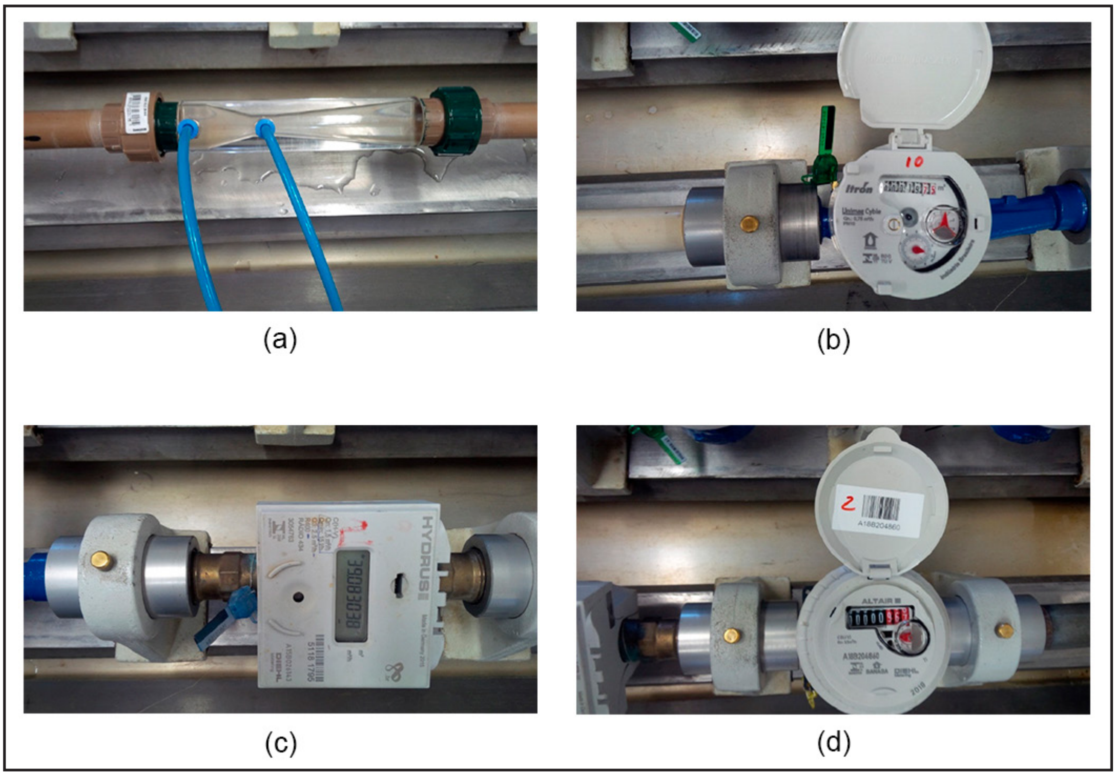
A pressure transducer (Figure 4) from the SMAR brand, model LD 301, was used in association with the Venturi tube. This is an intelligent transmitter used for measuring differential pressure, absolute pressure, gauge pressure, level, and flow. The model used is the D3 with maximum range -36 to 36 psi, powered by a 12V source. For this test, the meter has been adjusted to operate in the range from 0 to 100 mmH_2O, with accuracy of 0.2%. All data were collected through the Sensus data logger, connected in series with the pressure transducer, operating from 4 to 20mA.

The Venturi tube was connected to a pressure transducer through the pressure taps shown in Figure 5 (a), arranged according to the ISO 5167-1: 2022.

Figure 4 – Differential Pressure Meter

Figure 5 – (a) Venturi tube with pressure taps; (b) Tachymetric flowmeter; (c) Ultrasonic flowmeter; (d) Volumetric flowmeter



Source: Authors’ private collection (September 2024)

Figure 5 (b) shows the velocimetric meter, produced by Itrón, Unimag Cyble type, which is an extra-dry single-jet turbine water meter for residential applications, the one used in the test was 20 mm in diameter size for cold and hot water. Start of operation with 8 l/h, minimum flow of 15 l/h, transition flow of 60 l/h, rated flow of 0.75 m^3/h and max flow of 1.5 m^3/h. The ultrasonic meter (Figure 5 (c)), by Diehl metering, Hydrus type, with 20 mm in diameter, is a static ultrasonic water meter for measurement and recording in all water supply applications. Start of operation with 2.6 l/h, minimum flow of 15 l/h, transition flow of 25.6 l/h, rated flow of 1.5 m^3/h, max flow of 3 m^3/h. The volumetric flow meter (Figure 5 (d)) used is produced by Diehl metering, type Altair, with 20 mm diameter, is a water meter with precision in low flow. Start of operation with 2 l/h, minimum flow of 15 l/h, transition flow of 22.5 l/h, rated flow of 1.5 m^3/h and max flow of 3 m^3/h.

In this work, indication deviations between the Venturi meter and the other flowmeters were analyzed, as well as uncertainties, using Equation [5] (Peng et al., 2012; ISO/IEC 98-3:2008). The indication error, Di, expressed as a percentage, is given by:

$$\frac{(Vi-Va)}{Va}\cdot 100 = Di \qquad (5)$$

where "Vi=Rf-Ri" is the water volume measured (where, Ri = initial reading and Rff=final reading)

"Va" is the volume determined by volumetric tank apparatus.

Vi" is the score volume in the meter's display which is noted as the value of the measured quantity and "Va" is the volume as the value of the reference quantity. According to ISO 98-1:2009, the flow uncertainty, dQ , for the Venturi meter is expressed by Equation (6), where H represents the differential pressure value. All measurement values are given in SI units (International System of Units)

$$dQ = \pm\sqrt{\left(\frac{3{,}53\times10^{-5}}{H^{0{,}49376}}\right)^2} \qquad (6)$$

Zhang et al. (2019) point out that the pressure difference in the Venturi tubes affects efficiency considerably. Several parameters, such as nozzle inlet length, cone aperture angle, nozzle throat section length, nozzle outlet dimensions, diffusion section inlet and outlet length and diameter, also influence work performance.

During the tests, to ensure a fully developed flow profile, the meters were installed according to the most restrictive recommendations found in the literature. Specifically, in the upstream section of the flowmeters, a straight pipeline 0.5 m in length (equivalent to 20 diameters) was installed, in accordance with AWWA (1989) guidelines.

According to ISO 5167-1:2022, the relative uncertainty of the discharge coefficient, C, is equal to 1% and must be considered in the flow rate calculation. An additional uncertainty of 0.07%—relative to the volume of the bench—was calculated due to the operation of the volumetric test bench. This value accounts for the variation in tank volume caused by thermal expansion of the tank material (stainless steel).

To express pressure in meters of water column (mH_2O), the local acceleration due to gravity in Campinas (9.7845 m/s^2) was applied. In some tests, calibration of the Venturi tube was performed by adjusting the discharge coefficient based on the reference flow of the volumetric test bench, according to the measured volume

All the average flow rates were calculated, as well as all flow deviations from the values calculated by the standard volume tank. All tests and trials were carried out considering the standard volume values of the bench, and in all tests the meters were evaluated simultaneously. The test flow rates were 10 l/h, 22.5 l/h, 40 l/h, 100 l/h, 250 l/h, 450 l/h, 700 l/h and 1000 l/h.

Two adjustments were considered for the Cd factor of the Venturi tube, referred to as Adjustment 1 and Adjustment 2. In Adjustment 1, the Venturi *Cd* factor is based on theoretical coefficients for calculating the discharge coefficient and assumes a single Cd_{ex} value for the entire flow range of the meter. In Adjustment 2, the Cd_{ex} values were determined through volumetric calibration of the Venturi tube. In this case, two distinct functions of Cd_{ex} as a function of the Reynolds number, were considered for two separate flow ranges.

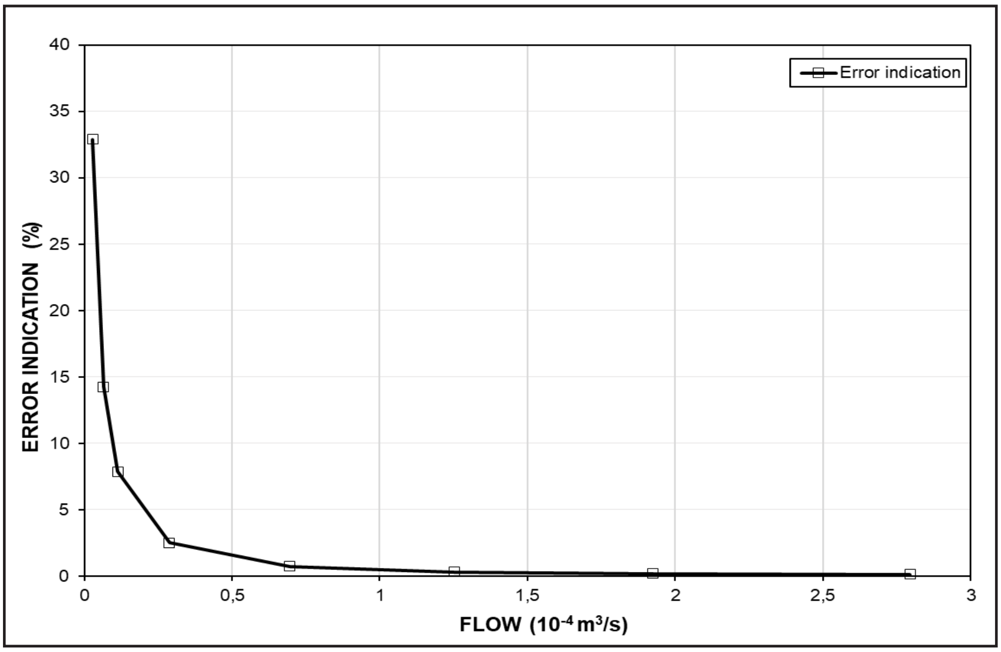
4 RESULTS AND DISCUSSIONS

4.1 First Venturi Adjustment

The first adjustment was developed using the standard coefficient of discharge for Venturi Tube provided by literature, being calculated based on ISO 5167-4: 2022. This coefficient called *Cd*=0.9792 was used fixed for all ranges of pressure differential readings by the pressure transductor associated with the primary device.

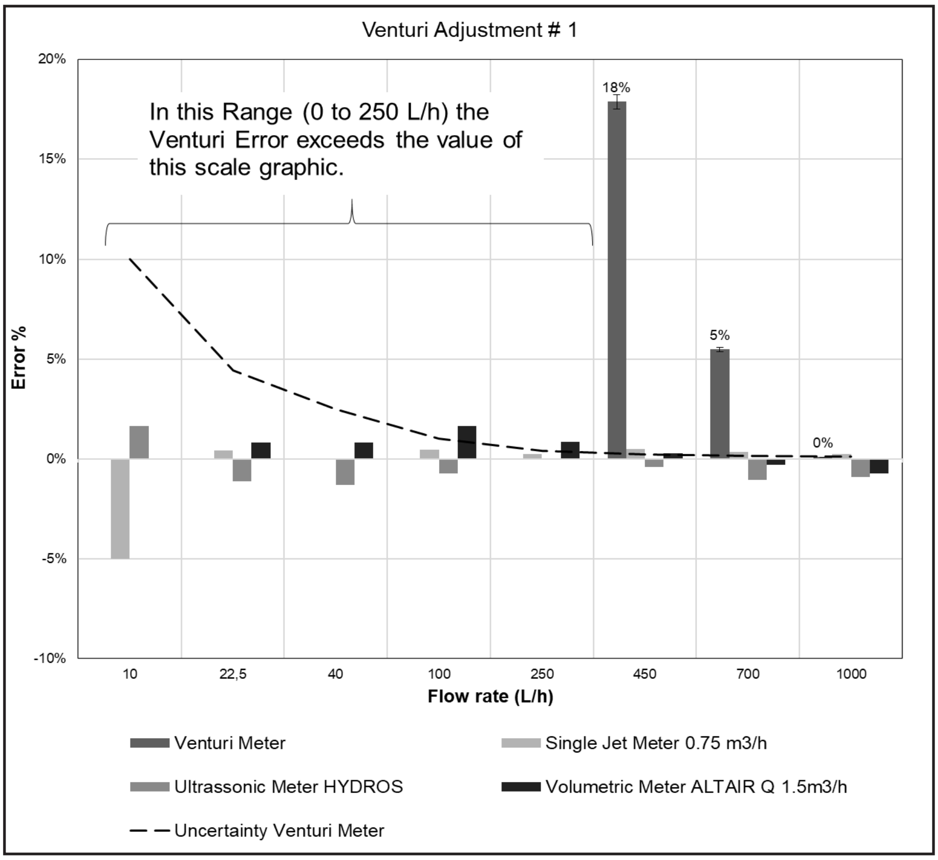
Figure 6 shows these results in relation to the volumetric bench test. Figure 7 presents the same test, but with a comparative evaluation of the other flowmeters, using the Cd coefficient. It is evident that, under these conditions, the Venturi meter produces good results only at the highest flow rate..

Figure 6 – Error results of Venturi Tube by Volumetric method in first scenario and discharge coefficient Cd



Source: the authors (2025)

Figure 7 – Error results of Venturi Tube by Volumetric method in first scenario – with all meters

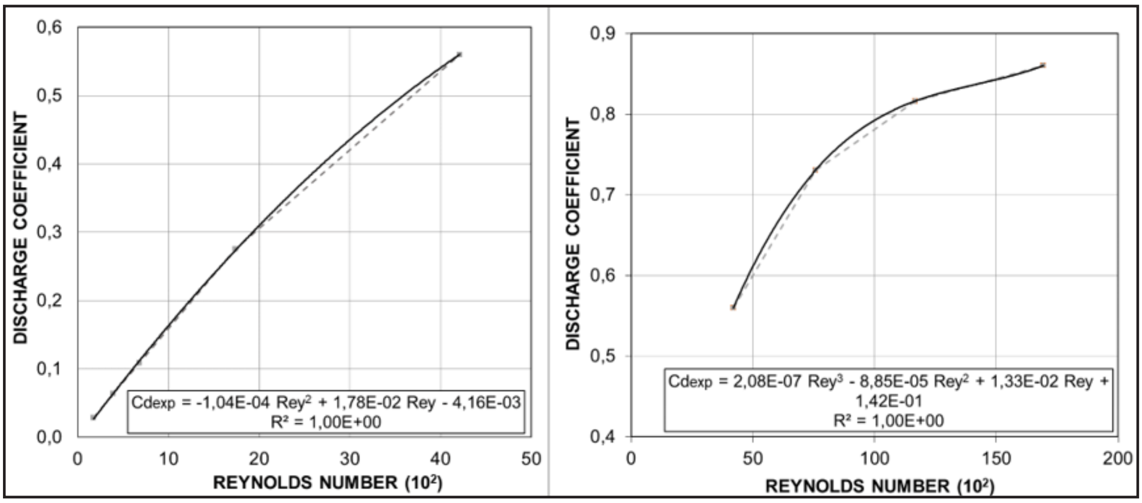


Source: the authors (2025)

4.2 Second Venturi Adjustment

The second adjustment was developed using the variable coefficient of discharge for Venturi Tube provided by two experimental adjusted equations where Cd_{ex} is a function of Reynolds number (Cd_{ex}=f(Rey). The first one refers to the Range I (*Rey* $2x10^2$ *to Rey* $2x\ 10^3$) and the second one, to Range II (*Rey* $2x10^3$ *to Rey* $1.8x\ 10^4$). Different pressures were also considered. Figure 8 (a) and (b) shows the relationship of the Cd_{ex} coefficient and the Reynolds number, for each range with respective equations. The aim of both equations is to minimize the flow reading deviations of the venturi meter based on the volumetric bench test. Therefore, using both equations (depending on Reynolds range) to obtain the Cd_{ex} it is possible to adjust a minimum error curve for the Venturi meter.

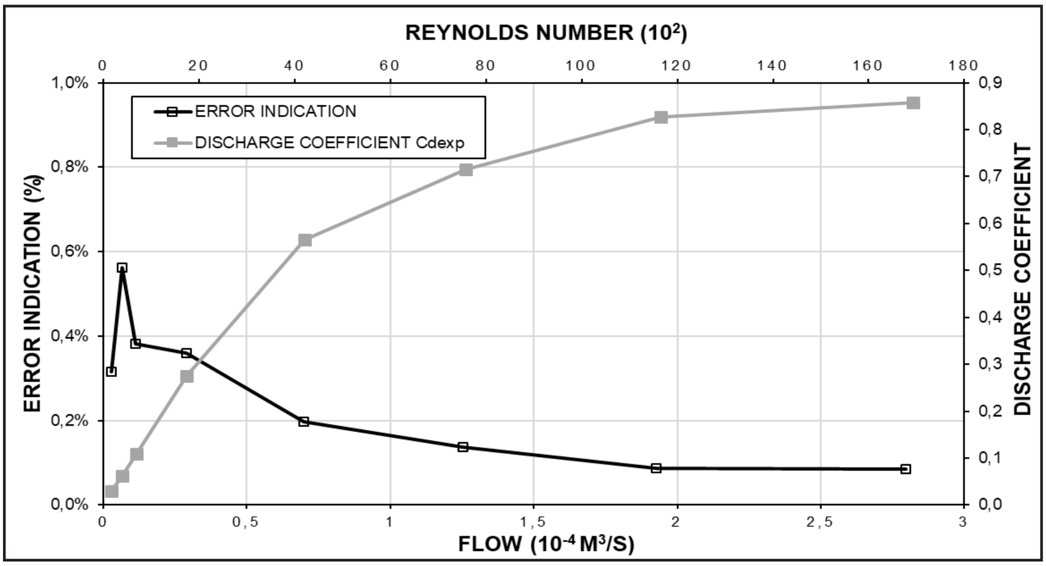
Figure 8- Coefficient of Discharge Vs. Reynolds Number - Range I (a) - Range II (b)



Source: the authors (2025)

Figure 9 presents an adjusted curve for Cd_{ex} proposed by this study to minimize the reading error of Venturi in relation to the standard volumetric bench test. The curve is presented here continuously relating Cd_{ex} with Reynolds number and flow with error indication.

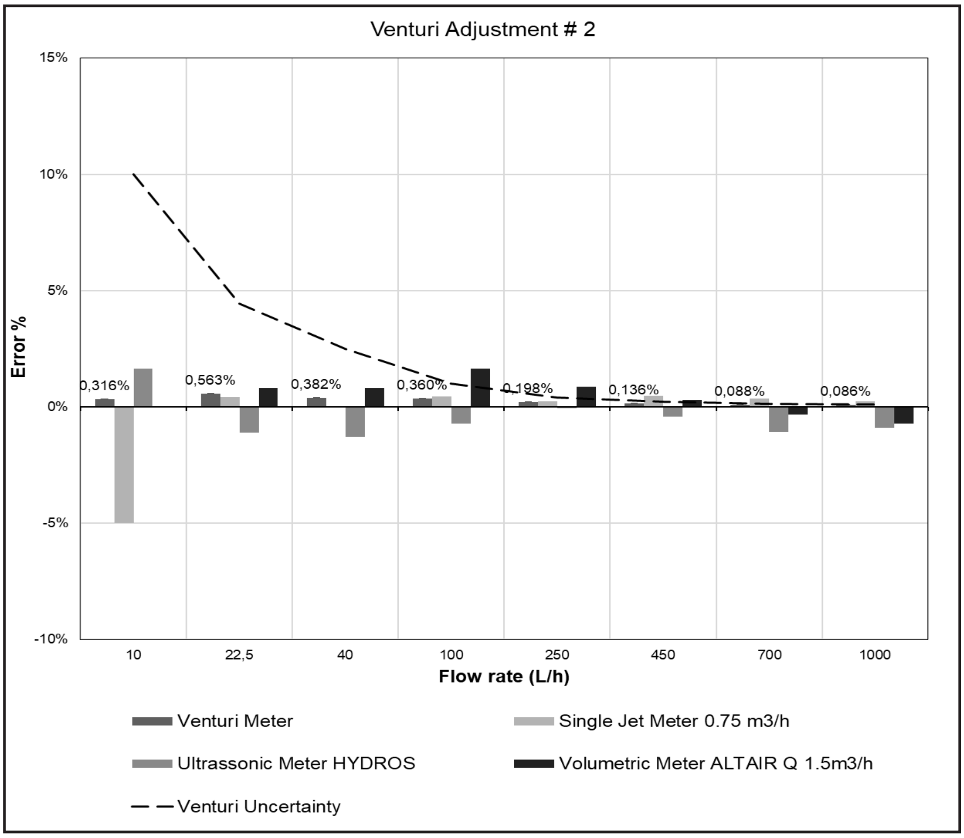
Figure 9 – Discharge Coefficient Cd_{ex} and Venturi indication error



Source: the authors (2025)

Figure 10 shows these results, in comparison to the other flowmeters. Since all the meters used were evaluated in the test bench, by volumetric method, it is evident that under this condition the Venturi tube shows good results over a slightly larger flow range.

Figure 10 – Error results of Venturi Tube by Volumetric method in second scenario – with all flowmeters



Source: the authors (2025)

Figure 10 represents the global results of the tests perform with all meters used in this study in comparison with the volumetric bench test. Here, the adjusted Cdex (as presented on Figure 9 (a) and (b)) for the Venturi meter is considered. The result from the Venturi presents a superior performance (regarding reading error) in relation to the volumetric and velocimetric (Single Jet) and similar or superior performance to ultrasonic meters.

5 CONCLUSIONS

The Venturi meter shows deviation results in relation to the volumetric bench in the order of +2.32% to -1.84%, with average performance around 0.26%.

The results obtained show, as expected, low performance of the Venturi meter for low flow rates. However, the result of Venturi is positive for medium and high flows. This behavior is especially evident when considering a fixed, theoretical discharge coefficient. However, for the tests performed using the adjusted Cd_{ex} coefficient—calibrated with the volumetric test bench—the results were superior when compared to those of the other meters.

In general, the results obtained show that the Venturi tube could be used for residential measurement, provided it is combined to a pressure gauge with an appropriate scale, and considering the variable Cd_{ex} coefficient. Evidently, using a variable Cd_{ex} requires data processing by the meter's secondary element (the pressure transducer); however, this can be performed by the equipment before displaying the instantaneous flow rate and total volume consumed.

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