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Experimental Investigation for Local Tank Inflow Model

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Abstract

In the present paper the effect of private roof tanks and of the float valve characteristics on apparent losses due to water meter errors was investigated via an experimental study. The tests were carried out at the Environmental Hydraulic Laboratory of the University of Enna (Italy), on a high-density polyethylene (HDPE 100 PN16) looped distribution network. The experimental results showed that network pressure plays an important role in the characterisation of the floating ball valve emitter law, but the tank operating condition is the most relevant aspect to be considered mainly for water meter error evaluation.

Keywords: Laboratory tests; float valve; local tank modelling.

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1. Introduction

In keeping with the adage "out of sight, out of mind", the water distribution system has been neglected in many water utilities and losses from water distribution systems have been a worldwide problem. They have become of particular importance in water-stressed countries. To reduce these losses and improve efficiency of water distribution systems, tools and methods have been developed over the years.

The International Water Association (IWA) has done pioneering work in the field of best practices to reduce and classify water losses. The IWA developed a water balance that classifies water entering a distribution system into authorized consumption and water losses [1] ,[2]. Water losses are further classified as real and apparent losses.

Apparent losses are not physical but financial losses that result in a reduction of revenue. They are often the most expensive water losses encountered by a distribution system and consist of water volumes withdrawn from the

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network, consumed by users but not paid for. Thus, water that is not accounted for may have an effect on the water balance and revenue of the water utility [3].

Apparent losses are a result of unauthorized consumption and meter inaccuracies [1], [2]. Unauthorized consumption is caused by illegal behavior, where users take water from the network without authorization. Meter inaccuracies include meter reading, billing errors and meter under-registration. Reading and billing errors are typically caused by human errors. For instance, the meter may be misread and incorrect information may be transferred to the billing department of the water utility. This type of error can be reduced improving the internal procedures of the utility. Errors in meter registration are caused by intrinsic inaccuracies affecting the water meter.

User meters are generally required to record volumetric totals for billing purposes and overall water system management: these meters provide indispensable data used by the utilities for issuing bills, computing the system water balance, and identifying network failures, water theft and anomalous user behavior. Therefore, the utilities rely on these instruments for both the technical and economic management of their water systems. As above mentioned, water meters are subject to intrinsic errors, that are responsible for apparent losses actually caused by meter under-registration. The water utilities, thus, does not receive appropriate compensation for the service provided.

Water meters are designed for a specific flow rate, which is called the permanent flow rate, Q_3. The meter should be able to work at the permanent flow rate (or a lower flow rate) continuously for its design life without exceeding the permissible error. Although a meter is designed for the permanent flow rate, the actual flow through a meter is not constant, but varies a great deal. Thus water meters should not only be accurate at the permanent flow rate, but over a wide range of flow rates. The relative error of a meter is not the same for the full flow range of a water meter. Mechanical meters tend to under-register at low flow rates and over-register at higher flow rates. The graphical representation of the variation in relative error with the flow rate is known as the error curve.

The international standards [4] that specify the required accuracy of water meters have to take the typical error curves into account. Thus, they specify the maximum permissible error (MPE) of a meter as an outline or ‘envelope’. The maximum permissible error is the largest relative error that is allowed, irrespective of whether the error is positive or negative. The maximum permissible error envelope is divided into two zones called the lower and upper zones respectively, and the meter is allowed to have a larger error in the lower zone ±MPE_L) than the upper zone (±MPE_U). ISO 4024:2005 specifies a maximum permissible error equal to ±5% in the lower zone, and ±2% in the upper zone. The lower zone includes flow rates between the minimum flow rate, Q_1, and the transitional flow rate (excluded), Q_2; the upper zone is defined as flow rates of between transitional (included) and overload flow rate, Q_4.

For flow rates lower than the minimum, the error curve steeply decreases but does not reach the axis of ordinates, which effectively means that there is a flow rate for which the meter does not register any volume. As the water moves across the meter sensor, it pushes against the sensor in an attempt to move it. However, the sensor is held back by friction forces, and at very small flow rates the water cannot overcome these friction forces to get the sensor moving. Thus the sensor remains static and the meter does not register the small flow passing through it. As the flow rate increases, a value is reached where the water is just able to get the sensor moving and the meter starts registering a flow. This flow rate is known as the starting flow, defined properly as the flow that can generate motion in the meter when the mechanism is at rest. At this flow rate, the meter begins to measure the passing water volume, even if the accuracy is practically zero (i.e., the metering error is about -100%), which means that a lot of the flow through the meter will not be registered. This metrological parameter not only represents the starting point of the error curve but also is indispensable for determining the percentage of volume registered by a meter.

As the flow rate further increases, the meter error reduces and becomes positive, i.e. it over-registers the flow. The positive error increases for a while before it reduces again and stabilizes close to the zero-error line. This stable zone continues past the permanent flow rate and represents the ideal flow rate where the meter will produce the best results. While the meter is designed to operate continuously at the permanent flow rate, it is able to handle higher flows without detriment to the meter, as long as these higher flows last for only short periods at a time. The overload flow rate Q_4 should never be exceeded. If the flow rate through the meter is greater than the overload flow rate, even for a short period, the meter may sustain permanent damage.

Water meters deteriorate with use and generally under-register as they age [5–10]. The starting flows and accuracy at low flows are the areas on the accuracy curve that tend to deteriorate most rapidly. It is not possible to predict the evolution of the error curve with time, since there are so many factors that affect the way meters will lose their accuracy such as meter technology, volume through the meter, water quality, consumption profile of the user, installation conditions and meter parts composition ([5], [11], [12], among others).

Since errors vary throughout the measuring range, the amount of water not registered depends not only on the shape of the error curve but also on the consumption flow rates of the users. In order to estimate how much consumed water is not measured, both parameters need to be combined to calculate the weighted error of a meter, defined as the combined error at different flow rates, obtained considering the percentage of water that it is consumed at each flow rate. This parameter provides the amount of water, in percentage, that is not measured or measured in excess for every liter consumed [13].

Where users are served by way of roof tanks, the probability of meter under-registration is increased, because of the tendency for a greater part of the consumption of users to pass through the meter at low and very low flow rates ([7], [14], [15]). Private tanks are filled using a proportional float valve that opens partially or totally as a function of tank water level and network pressure. While the users receive a continuous supply, the tank is usually full, and the float valve opens as soon as the tank's water level falls. During periods of high consumption, the tank's water level drops, the float valve opens completely, and water enters the tank at a high flow rate. During periods of lower consumption, the water level does not fall as much, the valve opens only partially, and the flow rate passing through the meter and entering the tank is very low. The meter is thus forced to work in the lower part of its measuring range where error is very high. Furthermore, the slow closure of the float valve induces flows that are lower than the meter's starting flow and thus are not registered. When the users experience intermittent supply ([9];[10]), water flows into the tank only when the network pressure at the user connection is sufficient to supply the tank. When the network pressure is low, tank water levels drop to meet user needs, with tanks often almost empty by the time the network pressure increases. The float valve is, thus, completely open and water pass at a very high flow rate.

Apparent losses are influenced by network operating conditions and by network pressure and, for this reason, in the present study, an experimental laboratory campaign was carried out, in order to characterize the hydraulic behaviour of private tanks and their supply ball valves, to investigate water meter errors related to network pressure and to establish which network operating condition is more affected by apparent losses.

2. Experimental setup

The tests were carried out at the Environmental Hydraulic Laboratory of the University of Enna (Italy), on a high-density polyethylene (HDPE 100 PN16) looped distribution network. The network has three loops, nine nodes and eleven pipes DN 63 mm. Each pipe is about 45 m long and is arranged in almost horizontal concentric circles, with bends having a radius of 2.0 m, thus ensuring that the form-resistance losses due to pipe bend can be neglected. An overview of the network is plotted in Fig. 1. Four pumps (P) supply the needed discharge from the recycling reservoir to the upstream air vessel (AV), which behaves as a constant head tank, keeping the pressure constant and equal to a prescribed value by varying the speed of the pumps (total water head ranging from 10 to 60 m).

The system is monitored by 6 electromagnetic flow meters put in pipes 0-1, 1-4, 2-3, 4-5, 5-6 and 7-9 of the network. Pressure cells and multi-jet water meters are distributed over the whole network at each node position. Demands are assumed to occur at the node position. Four hand operated sphere valves are installed in pipe 1-2, 4-3, 6-7, 10-9, in order to control the flow in each loop. The network is designed to model the effect of real losses as well as apparent losses. Specifically, in order to study apparent losses due to the presence of private tanks in the distribution network, node 7 and node 9 are equipped with local tanks: node 9 is equipped with a rooftop tank (placed at 17.5 m above the network level) and node 7 is equipped with a ground level tank. Water demand occurring at the tank nodes can be modeled either considering that the tank is interposed between the user and the network or considering that the user is directly connected to the network. In the present research, we focused the attention on the first case using only the node 9 (with the rooftop tank) because apparent losses are largely influenced by the pressure over the tank inlet and the rooftop location of the tank can be considered the most critical condition in such types of intermittent networks. The water tank was located 15 m above the network level, thus to reproduce the effect of the private water tank usually installed by the users to cope with water scarcity condition. The tank is connected to the water distribution network by means of high-density polyethylene (HDPE 100 PN16) pipe 30 m long, with a diameter of ½". The tank filling process is governed by a float ball valve: the ball valve is totally open if the water depth in the tank is lower than 80 cm and it is totally closed once 1 m depth is reached.

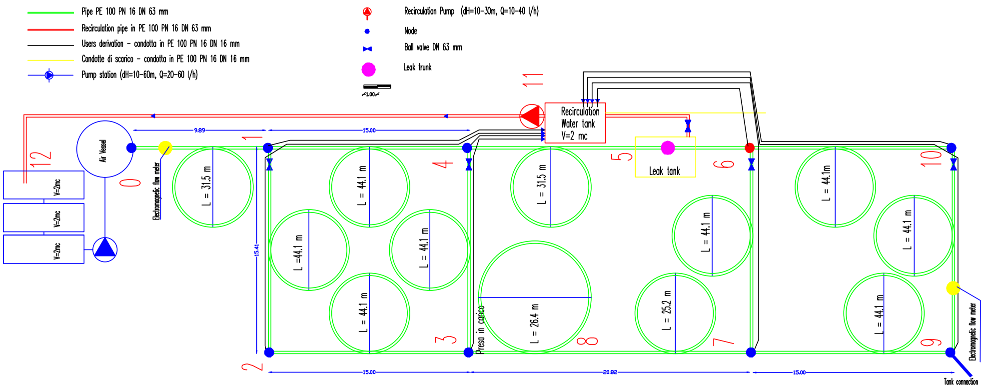

Fig. 1 Layout of the water distribution network.

Three types of experiments were carried out:

a) starting from the empty condition, the tank is filled considering the daily water supply of the user (350 l per inhabitant per day); this condition simulates a daily intermittent network in which the tank is filled every two days and it is emptied in the day in which water supply is not guaranteed;

b) the tank is by-passed and the user is directly connected to the network in continuous supply condition; this condition simulates the common operating condition of water distribution network;

c) starting from the full condition, the tank is constantly supplied by the network and it remains substantially full for all the time; at each water use, the ball valve opens slightly and the tank is rapidly replenished; this conditions simulates the presence of private tanks in networks that are constantly supplied.

To evaluate the water volume discharged into the private tank, two electromagnetic flow meters and a multi-jet water meter were used. The first flow meter is located in the inlet pipe of the network (see pipe 0-1 in Fig. 1) while the second is located close to the connection node between the network and the tank. On the other hand, the water meter was installed in the node supplying the private tank (node 9 in Fig. 1). The two electromagnetic flow meters have an accuracy of 0.1%. The pressure has been measured by means of a piezo-resistive pressure transducer, with a 6 bar full scale (f.s.) and an accuracy of 0.1% f.s., located at the connection node. In order to link the pressure to the flow discharge in the water tank seven different scenarios were reproduced, varying the pump pressure in a range 2.0-5.0 bar. The impact of pressure was only relevant in the condition (a), while it was less important in condition (b), because ball valve is always almost closed, and in condition (c), because user demand is marginally influenced by network pressure.

3. Experimental results and discussion

For all the test cases presented above measures were collected after 5 minutes from the experiment beginning, thus ensuring steady state conditions. Each test case was repeated twice and the average value was considered. In the following the experimental results are reported and discussed. Each experimental test was replicated two times in order to evaluate his repeatability. At the beginning, condition (a) was considered in order to evaluate tank behaviour in daily intermittent supply and to estimate the hydraulic parameters of the ball valve emitter law.

A node demand model was developed to assess the apparent losses associated with meter errors and private tanks. The model is able to simulate the tank filling process [16], the variability of tank inflow due to changes in the network pressure, float valve characteristics, measuring errors ([7]). Thus, the model was based on the tank continuity equation (Eq. 1), the float valve emitter law (Eq. 1) and the measuring error equation (Eq. 2):

$$Q_{up} - D = \frac{dV}{dt} = Adh \qquad with \qquad Q_{up} = C_v \cdot a \cdot \sqrt{2gP} \tag{1}$$

$$Q_{meas} = f\left(Q_{up}\right) = \begin{cases} Q_{meas} = 0 & if\ Q_{up} < Q_s \\ Q_{meas} = Q_{up} \cdot \left[1 - \frac{Q_s}{Q_{up}} \cos\left(\pi \frac{Q_{up} - Q_s}{Per}\right)\right] & if\ Q_{up} \geq Q_s \end{cases} \tag{2}$$

where D and Q_{up} are the user water demand and the water flowing from the network and entering the private tank, respectively; V is the volume of the tank having area A and variable water depth h; C_v is the float valve emitter coefficient, a is the valve effective discharge area, P is the hydraulic head over the distribution network, and g is the gravity acceleration; finally, Q_{meas} is the flow measured by the meter, Q_s is the meter starting flow, and Per is the semi-period of measurement error oscillation near zero, which both negative and positive errors to be accounted for, depending on passing water flows.

Float valve emitter coefficient C_v depends on the floater position, and thus on the water level in the tank according to the following empirical laws:

$$C_v = f\left(h\right) = \begin{cases} C_v = C_v^* & if\ h \leq h_{\min} \\ C_v = C_v^* \cdot \left(\frac{h_{\max} - h_s}{h_{\max} - h_{\min}}\right)^m & if\ h > h_{\min} \end{cases} \tag{3}$$

with h_{min} and h_{max} the water depths corresponding to open and closed valve, respectively, C_v^* the emitter coefficient of the fully open valve and *m* a shape coefficient, usually ranging between 0.5 and 2. C_v^* and *m* must be calibrated. Fig. 2 shows the impact of network pressure on the emitter law coefficients. The emitter parameter C_v^* of the open valve decreases with pressure depending on the increase of local headloss due to the valve. The variation is not linear and in the analysed case is well interpolated by the following power law:

$$C_v^* = C_{v0} + b \cdot \left(P - P_0\right)^{-n} \tag{4}$$

where C_{v0} is the horizontal asymptote equal to 0.276, P_0 is a vertical asymptote equal to 11.1 m; b and n are shape coefficients calibrated to 6.24 and 1.27, respectively. The variation of *m* is linear indeed according to the equation $m=0.0027P + 0.229$. The coefficients C_v^* and *m* are empirically estimated according to least square error method applied to the pressure – discharge data recorded at the network node 9. Fig. 3 shows the comparison of the modeled emitter law and recorded data in the performed experiments. Similar results were obtained in other cases.

Considering the good accordance of numerical model and recorded data, the emitter law equation was used to estimate apparent losses due to private tank in the three above-described operational conditions. The relative error of the installed water meter was obtained by the use of a standard test bench compliant with the above mentioned ISO standards. Fig. 4 shows the distribution of discharge values at the node 9, in the operating condition (a), and the relative metering error of the water meter. The tank is emptied and filled cyclically at each interruption of water supply, the serviced discharge is always quite high and the float ball valve is frequently completely open. At the test pressure of 2 bar, more than the 90% of the supplied volume passes through the water meter with discharges between 500 and 600 l/h for which the meter is characterized by over-registration (i.e. the indicated volume is higher than the actual volume). Increasing the test pressure (Fig. 3b), the discharges increase and the over-registration is even more evident.

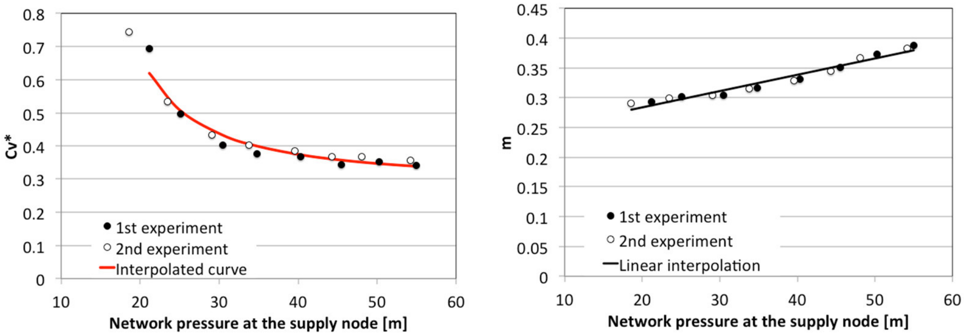

Fig. 2 Variation of emitter coefficients with the network pressure.

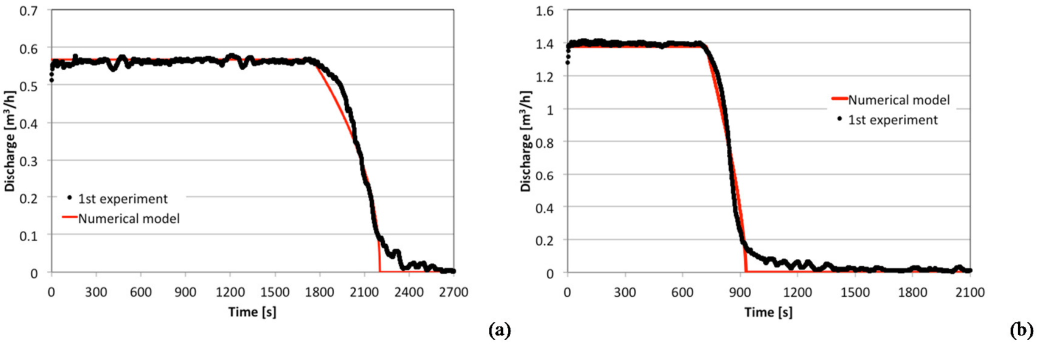

Fig. 3 Comparison between the modelled emitter law and experimental node discharge data. Network pressure 2 bar (a) and 5 bar (b).

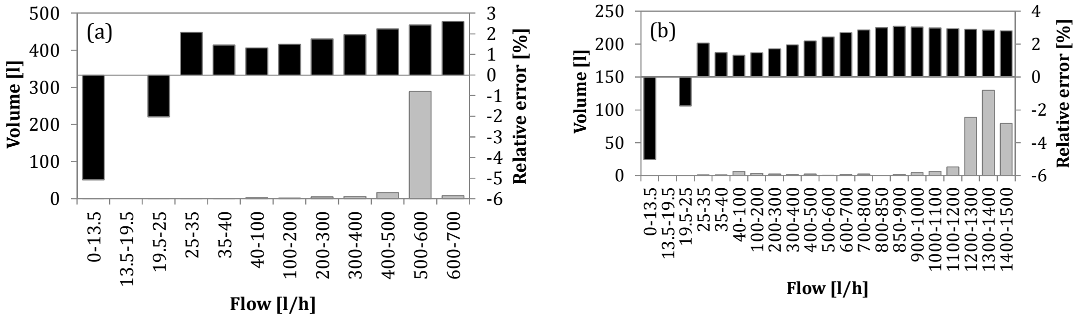

Fig. 4 Consumption profiles and relative error: (a) operating condition (a) pressure 2 bar; (b) operating condition (a) pressure 5 bar.

Table 1 shows the relative metering error and the total over-registration varying the test pressure. In all the cases, operating condition (a) takes to over-billing 2-3% of the supplied volume. This effect is due to the combination of high supplied discharges and low meter starting flow that is always lower than 5 l/h (Fig. 4). Similar analysis were performed in operating condition (b) and (c) in which the effect of network pressure is less evident because in one case the float ball valve is always almost closed and discharges entering the tank are very low and in the other case user's consumption is not really dependent on network pressure. Fig. 5a shows the user's consumption pattern and the relative error for each discharge interval. The daily supplied volume at low flows is relatively small and consequently meter over-registration is still present even if it is quite low (less than 1%). In the operating condition (c), when the private tank is present and always full, apparent losses can be found not accounting for more than 25% of the supplied volume at discharge lower than 10 l/h.

Table 1. Relative error for each test pressure.

Flow rate [l/h]	Relative error [%]						
	P = 2.0 bar	P = 2.5 bar	P = 3.0 bar	P = 3.5 bar	P = 4.0 bar	P = 4.5 bar	P = 5.0 bar
0-19.5	-5.086	-5.086	-5.086	-5.017	-5.017	-5.017	-5.017
19.5-25	-2.026	-2.026	-2.026	-1.754	-1.754	-1.754	-1.754
25-35	2.071	2.071	2.071	2.071	2.071	2.071	2.071
35-40	1.455	1.455	1.455	1.481	1.481	1.481	1.481
40-100	1.322	1.330	1.321	1.331	1.315	1.325	1.319
100-200	1.496	1.490	1.482	1.516	1.493	1.480	1.478
200-300	1.748	1.733	1.736	1.734	1.732	1.749	1.719
300-400	1.960	1.980	1.978	1.917	1.966	1.926	1.951
400-500	2.243	2.214	2.203	2.211	2.171	2.168	2.199
500-600	2.436	2.424	2.396	2.420	2.436	2.421	2.437
600-700	2.601	2.678	2.617	2.652	2.611	2.659	2.698
700-800		2.853	2.857	2.860	2.920	2.861	2.870
800-850		3.035	3.053	3.034	3.031	3.034	3.012
850-900		3.071	3.067	3.071	3.071	3.071	3.071
900-1000			3.051	3.020	3.027	3.025	3.042
1000-1100				3.004	2.975	2.984	2.984
1100-1200						2.939	2.937
1200-1300						2.895	2.895
1300-1400						2.861	2.850
1400-1500							2.815
TOT	2.391	2.776	2.975	2.975	2.900	2.830	2.791

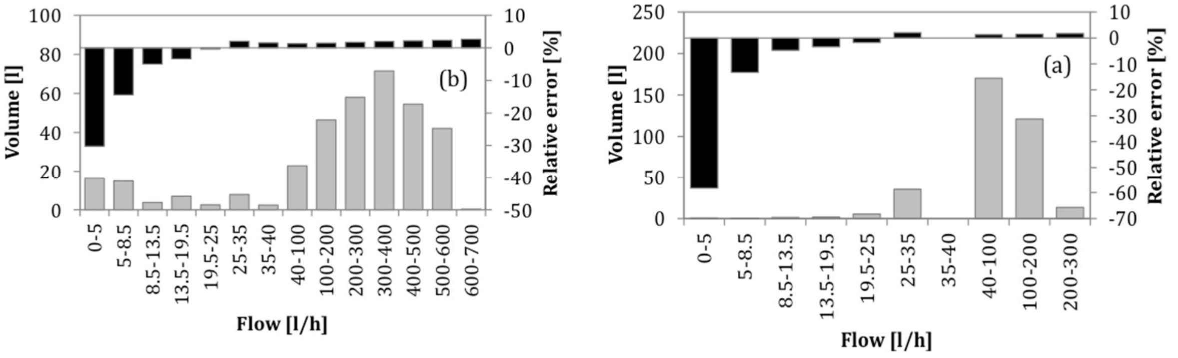

Fig. 5 Consumption profiles and relative error: (a) operating condition (b); (b) operating condition (c).

4. Conclusion

The proposed experimental study evaluated the apparent losses that can be due to the combination of turbine meter errors and the presence of private tanks. Different operating conditions were examined considering the presence of constantly filled tanks, the presence of tanks subjected to cyclical filling and emptying processes and the absence of the tank. Network pressure plays an important role in the characterization of the floating ball valve emitter law, but the tank operating condition is the most relevant aspect to be considered.

If the tank is subjected to cyclical emptying and filling, as happens in intermittently operated networks, pressure influences the parameters of the valve emitter law but supplied flows are so high that metering errors are quite low and usually positive, leading to general over-registrations in the range of 2-3%. Apparent losses were indeed found when the tank is always almost full. In such cases, the supply discharges are usually small because they have only to replenish the tank after a water use. In such operating conditions, metering errors are negative and a part of the supplied water volume is not metered taking to apparent losses.

The experimental results were obtained in a specific valve and tank combination. More studies should be carried out modifying some of the characteristics of the system in order to confirm the structure of the obtained experimental laws.

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