EXPERIMENTAL DETERMINATION OF THE DISCHARGE COEFFCIENT THROUGH CIRCULAR ORIFICE IN PVC PIPES

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ABSTRACT:

Real water losses derived from water supply systems represent an important topic, nowadays. It is difficult to predict and to calculate the water lost volume, these values being crucial in any water balance. In addition, the leakage flow can be estimated only when the geometric and hydraulic characteristics of the pipes and the period of time associated to the leakage are known. Also, by using the equation of the water flow can be obtained inaccurate values, especially when incorrect values of discharge coefficient are used. The values of the discharge coefficient can vary between 0.6 and 0.85, depending on a multiple aspects, such as the pipe diameter, the orifice size and shape, the pipe material, the orifice position on the pipe wall, the pipe thickness and the hydraulic parameters of the water (flow and pressure). This paper is focused of an experimental study of a leak simulation in a PVC pipe. Thereby, a circular orifice is drilled on PVC pipe wall and the influence of the water flow and pressure on the discharge coefficient (*Cd*) is analysed. The experimental values obtained for de *Cd* are 0.59 - 0.86, values that are in accordance with the results from similar studies.

1. INTRODUCTION

Worldwide, an important aspect in the management of a water supply and distribution system is the real water losses; aspect arises mainly due to the ageing and deterioration of the pipes while the water demand of potable water is constantly growing (Mckenzie, R., Seago, C., 2005). These losses are particularly given by the damaged pipes, unauthorised consumption, damaged flow meters and unbilled authorized consumption.

The real water losses derived from these systems already reach alarming levels in several cities around the world (IWA, 2019). Moreover, in ratio with the total water loss, the real losses represent sometimes over 70% (WHO, 2001). The water loss will lead to the decrease of the water suppliers' income and to a negative level of water services delivered to the consumers. Without these incomes, the water infrastructure will decline creating in this way a descending spiral from which it will be harder to exit.

One of the most effective methods used to reduce the water losses, only for short periods of times is the control of the pressure. By reducing the water pressure, the general status of a network pipes will not be improved (the water losses will do exist), but it will reduce the water volume flow out from the network and it will prevent the forthcoming of a new failure (J. Thornton, A. Lambert, 2005).

An important step in the determination of the water losses is a close monitoring of water distribution systems and therefore it can be reached a quick detection and intervention time on an inherent failure. In this way the water volume lost from this failure will be reduced.

The volume of water flow out from the pipe is an important parameter in the water balance (Mckenzie, R., Seago, C., 2005). This volume can be calculated if the discharge flow is known, by using the equation:

$$V_{NRW} = \frac{Q_{NRW}}{t} \quad (1)$$

where: V_{NRW} is Non Revenue Water (NRW) volume, [m^3];
Q_{NRW} = discharge flow, [m^3/s];
t = estimated time from the set off the alarm until the cut off the water supply in the network, [s].

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The relation that characterizes the water flow through orifices (L. Marian, M. Muste, 1993, J. E. van Zyl, 2014) gives the value of the discharge flow:

$$Q_{NRW} = C_d \cdot a \cdot \sqrt{2 \cdot g} \cdot P^{N_1} \quad (2)$$

where: N_1 is leakage exponent, usually set between 0,5 and 2,79 (Nourhan Samir, 2017). The value of the exponent is influenced by type of the orifice, the thickness of the pipe wall, the pipe elastic modulus and the flow regimes (F. De Paola and M. Giugni, 2012). The recommended value for rigid walls pipes and turbulent flow is $N_1 = 0.5$ (R. Gomes, J. Sousa and A. S. Marques, 2013, J. Thornton, A. Lambert, 2005, IDELCHIK I. E, 1994), value that was adopted in this study.

a = area of the leakage orifice [m^2]; the orifice is considered to be circular so, $a = (\pi \cdot d^2) / 4$;
d = diameter of the orifice, [m];
g = gravitational acceleration, $g = 9.81$ m/s^2;
P = pressure in the axis orifice, [mH_2O];
C_d = discharged coefficient (dimensionless).

The equation (2) clearly shows the dependence between the discharge flow and the discharge coefficient, C_d.

The technical literature refers to the discharge coefficient either by using the symbol C_d or the symbol μ. Due to this aspect, the discharge coefficient can be given by the relation (3) or (3'):

$$C_d = C_C \cdot C_V \quad (3)$$

$$\mu = \varepsilon \cdot \varphi \quad (3')$$

where $\varphi = C_V$ represents velocity coefficient calculated with the equation (David Prohaska, 2008, L. Marian, M. Muste, 1993):

$$\varphi = \frac{1}{\sqrt{1+\xi}} \quad (4)$$

where ξ is the pressure loss coefficient at the circular orifice while $\varepsilon = C_C$ is the coefficient of contraction and it represents the ratio between cross-sectional area of the water jet (a_c) and the orifice area (a):

$$\varepsilon = \frac{a_C}{a} \quad (5)$$

It is to be mentioned that the value of the coefficient a_c is always smaller than the value of the orifice area, a, and the value of the coefficient ε is sub-unitary.

The behaviour of the water flow, in case of a leakage is shown in figure 1. It can be seen that, right beside at the orifice output, the fluid jet will bear at the beginning a contraction, after which the fluid will bear a decompression and at the end it will expand all over the section (M. E. Taslim and S. Ugarte, 2004).

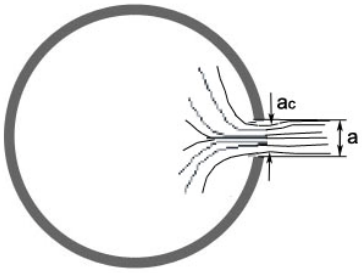


Figure 1. Water jet at the orifice output

Accordingly to the figure 1, the value of the coefficient ε depends on the size and shape of the orifice, the size of the contraction, the position of the orifice on the pipe wall and the flow regime via Reynolds criteria (Georgescu A. M., Georgescu S. C., 2007):

$$Re = \frac{V \cdot d}{\nu} \quad (6)$$

where V is mean velocity in the orifice section, [m/s];
ν = kinematic viscosity of the fluid, [m^2/s].

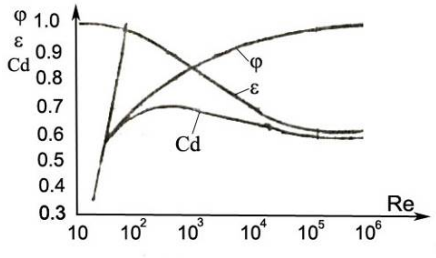


Figure 2. Contraction, velocity and flow coefficients values in function of the flow regime for smaller orifices (L. Marian, M. Muste, 1993)

Figure 2 shows the variation of the contraction, velocity and flow coefficients in function of the flow regime, it is a nomographic chart established on the experimental research. From this chart it results that the values of the C_d coefficient increase with the increase of the Re up to Re ~ 10^3, than the C_d values gradually decrease until the Re >10^5. For greater values of Re the value of the C_d coefficient is almost constant, $C_d \cong 0.6$.

In recent studies (regarding the dependence between the C_d coefficient and Reynolds number) similar curves where obtained (David Prohaska, 2008, Tingchao Yu, 2019), but the variation range for C_d was wider, between 0.6 and 0.85.

Comparing the relation (2) and (3) it results that the values of C_d coefficient are more difficult to obtain with the relation (3) because of the value of a_c which is very hard to acquire experimentally. For this study the relation (2) was used and the Q_{NRW} and P values were experimentally obtained.

2. MATERIALS AND METHODS

2.1 Experimental apparatus

The experimental setup used in this study has two units: the hydraulic bench and the mobile bench. The hydraulic bench has a 165 l water tank, a variable speed pump and a flow control gate (see figure 3). The mobile bench is a vertical mounted aluminium board with different types of pipes in terms of diameters and roughness (see figure 4). This experimental setup was used to analyse the variation of the water flows and pressures in a PVC pipe and to measure the water volume lost through a circular orifice, drilled into the pipe wall.



Figure 3. Experimental setup: the hydraulic bench

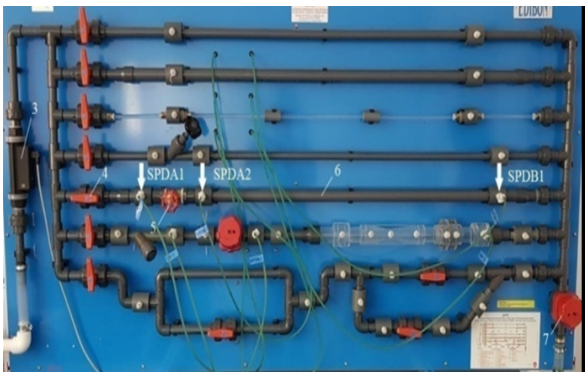


Figure 4. Experimental setup - the mobile bench

The elements of the experimental bench are: a pump start/stop unit (1), two flow control gates (2 and 7), a flowmeter (3), a ball valve (4), a gate valve (5), a PVC pipe with inner diameter of D=27.2mm (6) and three pressure sensors SPDA1, SPDA2 and SPDB1.

2.2 Experimental procedure

All sets of measurements were conducted on the PVC pipe, the element (6) on the experimental bench. The dimension of the pipe is 32x2.4mm with an inner diameter of 27.2mm. The flow gate is installed on the water supply pipe and it is used to measure the water volume circulated on the PVC pipe (element 6) when all the ball valves are closed, except the ball valve - element 4. In this manner the water volume was distributed only into the PVC pipe, the element (6).

Three sensors pressure, SPDA1, SPDA2 and SPDB1 were placed on the testing PVC pipe. SPDA1 and SPDB1 are used to measure the water pressure at the beginning and the end of this pipe and the SPDA2, placed between the SPDA1 and SPDB, is used to measure the pressure into the pipe section. On the opposite side of the vertical board, the SPDA2 has an air-release valve coupled with a plastic pipe. In order to simulate a leakage through a circular orifice, this air-released valve was used. In this way an orifice of a regular, circular shape with an inner diameter of 2.6mm was obtained.

The flow and pressure parameters were measured and acquired with the SACED /Edibon –soft.

The first set of tests were conducted to analyse the fluctuation of the C_d coefficient with the water flow and for this purpose the following step was completed:
Step 1: flow control gate (element 7) fully opened:
- with all the ball valves closed but the valve on the testing pipe, the pump is started.
- the flowrate is set to 20 l/min on the testing pipe:
1. for t = 30sec. the air-released valve is left closed and with the SPDA1, SPDA2 and SPDB1 sensors the pressure values are measured.
2. also, for t = 30sec. the air-released valve is left opened and the entire water volume passing through the plastic pipe is collected, then the valve is closed. The collected volume (V_{NRW}) is measured with a graduated recipient.
- the flowrate is increased with a set of 2 l/min up to 38 l/min and for 30 sec. and the values of measured pressure and V_{NRW} volumes are recorded. The recorded data are presented in figures 5 and 6.

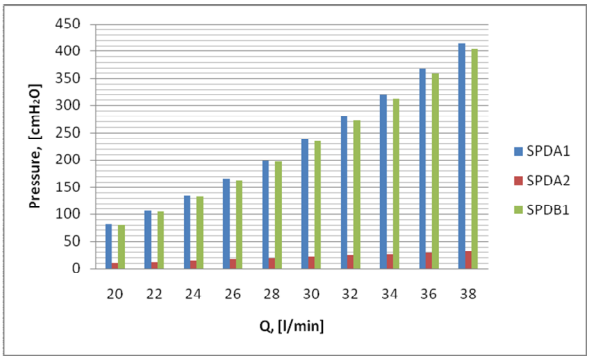


Figure 5. Measured values (step 1)

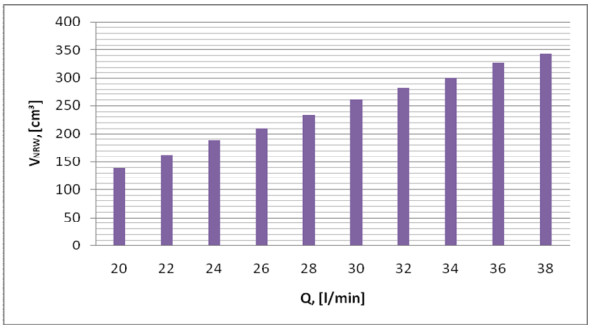


Figure 6. V_{NRW} values at the step 1 of the experiment

The set of sets 2 and 3 are carrying out to study the influence of the pressure over the C_d coefficient. In these cases the operating pressure is increased by partially closing the flow control gate (element 7).

The steps 2 and 3 imply the same operations as the step 1 except the fact that at step 2 the flow control gate (element 7) was partially closed - 5 rotations and at step 3 the same control gate was partially closed - 10 rotations. By following the same operation as in step 1, the influence of the pressure on the C_d coefficient is more obvious. The measured values for step 2 and 3 are presented in figures 7, 8, 9 and 10.

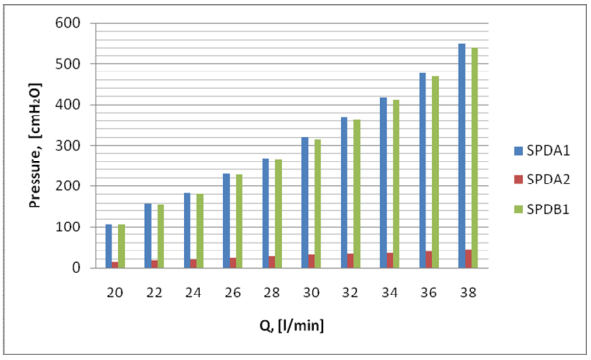


Figure 7. Measured values (step 2)

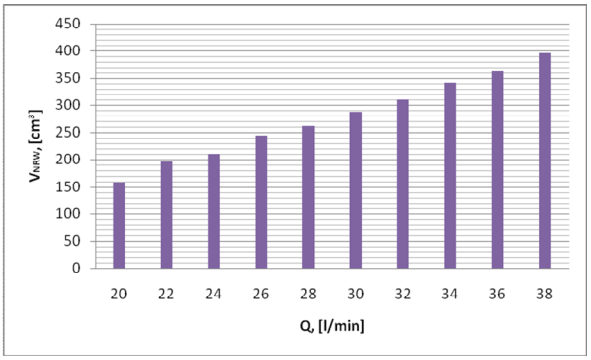


Figure 8. V_{NRW} values at the step 2 of the experiment

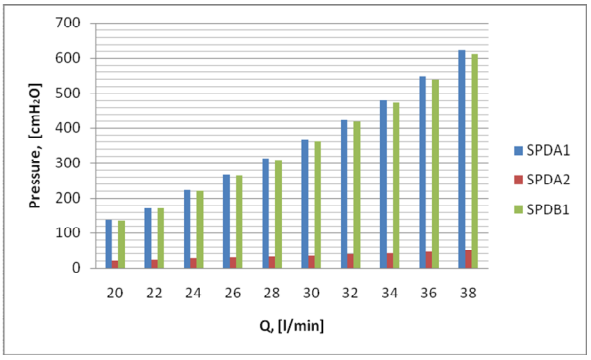


Figure 9. Measured values (step 3)

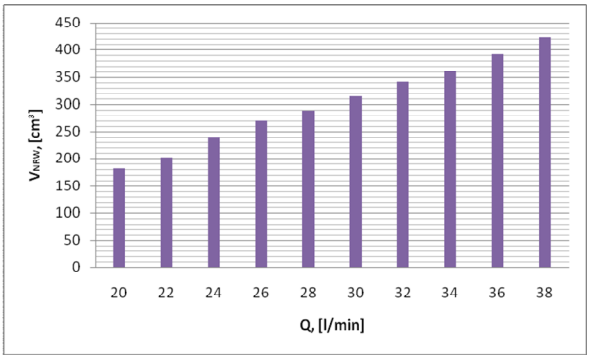


Figure 10. V_{NRW} values at the step 3 of the experiment

2.3 Data processing: calculus of *Cd* coefficient

By using the above measured values the C_d coefficient was calculated with the following equation (Van Zyl J.E. and Cri Clayton, 2007):

$$C_d = \frac{Q_{NRW}}{a \cdot \sqrt{2 \cdot g} \cdot P^{N_1}} \tag{7}$$

where:
- the discharge flow through the circular orifice is given by the equation:

$$Q_{NRW} = \frac{V_{NRW}}{t} \tag{8}$$

- the leakage exponent N_1 was considered to be N_1 = 0.5 (Lambert, A., Fantozzi, M., Shepherd, M., 2017),
- and for the values of the pressure P it was considered the values measured by the pressure sensor SPDA2 in mH_2O.
The results obtained by using the equation (7) are presented in table 1 and figure 11.

Table 1. Discharge flow and discharge coefficient calculated values

ID	Calculated values					
	Step 1		Step 2		Step 3	
	Q_{NRW} (l/min)	C_d	Q_{NRW} (l/min)	C_d	Q_{NRW} (l/min)	C_d
1	0.28	0.619	0.31	0.603	0.36	0.592
2	0.33	0.667	0.39	0.652	0.4	0.611
3	0.38	0.713	0.42	0.666	0.48	0.667
4	0.42	0.745	0.49	0.724	0.54	0.711
5	0.47	0.758	0.52	0.729	0.58	0.722
6	0.52	0.805	0.57	0.743	0.63	0.764
7	0.56	0.816	0.62	0.777	0.68	0.795
8	0.60	0.834	0.68	0.817	0.72	0.802
9	0.66	0.864	0.72	0.827	0.78	0.829
10	0.69	0.860	0.79	0.856	0.85	0.857

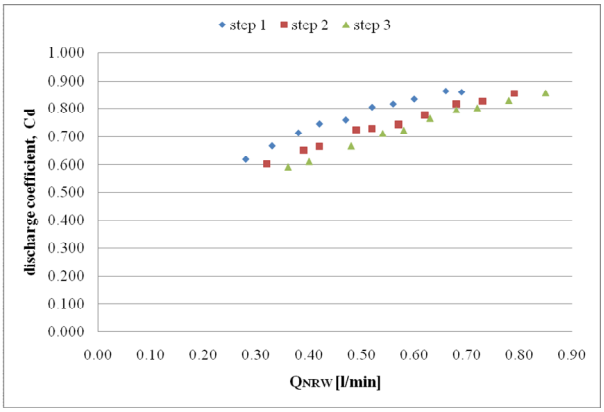


Figure 11. Influence of the discharge flow over the discharge coefficient

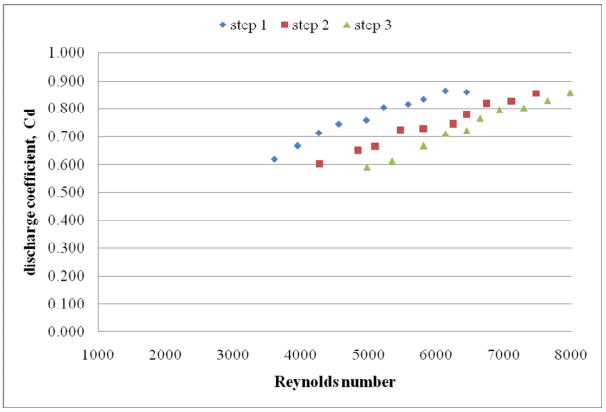


Figure 12. Discharge coefficient in function of the Re number

Furthermore, the influence of the pressure on the C_d it can be observed also in the values of the velocity in the orifice axis, values calculated with the equation:

$$V = \sqrt{2 \cdot g} \cdot P^{N1} \tag{9}$$

Another factor with a major impact on the C_d coefficient values is the Reynolds number, not directly, but via contraction coefficient. Hence, it became necessary to analyse this influence. So, by using the calculated velocity values with the equation (9) and by using the equation (10) (Coetzer, A., van Zyl, J., Clayton, C., 2006) it results the Reynolds numbers:

$$Re = \frac{V \cdot d}{\nu} \tag{10}$$

where: the value of the ν is considered to be $1.01 \cdot 10^{-6}$ m^2/s.

The results driven form the experimental data and from equations (9) and (10) are given in the table 2 and figure 12.

Table 2. Reynolds numbers and velocity calculated values

ID	Calculated values					
	Step 1		Step 2		Step 3	
	V (m/s)	Re	V (m/s)	Re	V (m/s)	Re
1	1.400	3604	1.657	4266	1.930	4970
2	1.534	3948	1.879	4838	2.080	5348
3	1.657	4264	1.981	5099	2.260	5814
4	1.771	4559	2.124	5468	2.390	6140
5	1.930	4968	2.259	5814	2.510	6450
6	2.029	5223	2.426	6245	2.580	6649
7	2.169	5583	2.506	6450	2.690	6936
8	2.257	5811	2.620	6746	2.840	7301
9	2.384	6137	2.766	7121	2.970	7649
10	2.504	6447	2.905	7477	3.100	7982

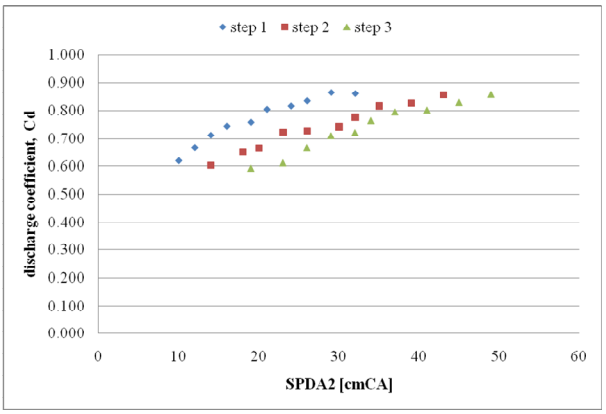


Figure 13. Discharge coefficient in function of the pressure in the axis orifice

As mentioned in the previous subsection (2.2), the pressure in the axis orifice represents a factor with a great influence on the calculus of the discharge coefficient. So, according to the conducted experiments and to the analytical results the diagram of discharge coefficient in ratio with the pressure in the axis orifice is drawn (see figure 13). It is important to say, that this diagram can be used in order to calculate the V_{NRW} values, but only in the same hydraulic and geometric conditions as those presented in this paper.

3. CONCLUSIONS

Based on the experimental and analytical analysis described in this paper the following conclusions emerge:

- ✓ the experimental values obtained for discharge coefficient are in the range of 0.59 – 0.86 and they are in accordance with the range of values indicated in the technical literature: 0.6 – 0.85;
- ✓ higher values of the supply flow drive to higher values of the discharge flow. As demonstrated in the subsection 2.3 equation (7), higher values of the discharge flow will lead to higher values of the discharge coefficient. In addition to this aspect it was shown, that this increase of discharge flow is attended by a slightly increase of the

pressure and therefore a greater influence on the flow regime via Reynolds number.

- ✓ as shown in figure (6) the proportional influence of the Re number on the C_d coefficient starts from $Re \sim 10^3$. This confirm the fact that the experimental values of C_d coefficient are on the ascending curve of the $C_d = f(Re)$ (see figure 2);
- ✓ by integrating the analytical results of the C_d coefficient into a graphical and tabular form, the water suppliers companies can easily evaluate the real water losses through a circular hole on the pipe wall by selecting the proper C_d value for each particular situation.

References:

De Paola, F. and Giugni, M., 2012. Leakages and pressure relation: an experimental research, *Drinking Water Engineering and Science*, 5, pp 59–65.

Gomes, R., Sousa, J. and Marques, A. S., 2013. The influence of pressure/leakage relationships from existing leaks in the benefits yielded by pressure management, *Water Utility Journal* 5, pp 25-32.

M. E. Taslim and S. Ugarte, 2004, Discharge Coefficient Measurements for Flow Through Compound-Angle Conical Holes with Cross-Flow, *International Journal of Rotating Machinery*, 10: 145–153.

Mckenzie, R., Seago, C., 2005. Assessment of real losses in potable water distribution systems: some recent Developments, *Water Science Technology Water Supply* 5(1), pp 33–40.

Nourhan Samir, Rawya Kansoh, Walid Elbarki, Amr Fleifle, 2017. Pressure control for minimizing leakage in water distribution systems, *Alexandria Engineering Journal*, pp 601-612.

Tingchao Yu, Xiangqiu Zhang, Iran E. Lima Neto, Tuqiao Zhang, Yu Shao and Miaomiao Ye, 2019. Impact of Orifice-to-Pipe Diameter Ratio on Leakage Flow: An Experimental Study, *Water* 11 (10): 2189.

Thornton, J., Lambert, A., 2005. Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships, *Proceedings of IWA special conference "leakage 2005"*, Halifax, Nova Scotia, Canada, September, pp 12-14.

Van Zyl, J. E., 2014. Theoretical Modelling of Pressure and Leakage in Water Distribution Systems, 16th Conference on Water Distribution System Analysis, WDSA 2014, *Procedia Engineering 89*, pp 273 – 277.

Van Zyl J.E.and Cri Clayton, 2007. The effect of pressure on leakage in water distribution systems, *Water Management* 160 (2), pp 109-114.

IDELCHIK I. E., 1994. *Handbook of hydraulic resistance* (3rd edition), Begell House, New York.

Marian, L., Muste, M., 1993. *Hidraulică şi maşini hidraulice, volumul I,* (*Hydraulics and Hydraulic Machines, volume I*), Cluj-Napoca, Ed. Lito Institutul Politehnic, pp 276-284.

Georgescu A. M., Georgescu S. C., 2007. *Hidraulica reţelelor de conducte şi maşini hidraulice, (Hydraulics of pipeline networks and Hydraulic Machines)*, Ed. Printech, pp 60-62.

WHO - World Health Organisation, 2001. *Leakage Management and Control - A Best Practice Manual*, WHO, Geneva, pp 19.

Coetzer, A.; van Zyl, J.; Clayton, C., 2006. *An experimental investigation into the turbulent-flow hydraulics of small circular holes in plastic pipes*, In Proceedings of the 8th Annual Water Distribution Systems Analysis Symposium (WDSA), Cincinnati, OH, USA, pp 27–30

David Prohaska, 2008. *Investigation of the discharge coefficient for circular orifices in riser pipes*, theses.

Lambert, A., Fantozzi, M.,Shepherd,M., 2017. FAVAD Pressure & Leakage: How Does Pressure Influence N1?, *IWA Water Efficient Conference.* IWA Water and Development Congress & Exhibition, 2019, Sri Lanka.