doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14857

EXPERIMENTAL ANALYSIS FOR THE LOSSES ASSESSMENT IN WATER DISTRIBUTION SYSTEMS

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Abstract

Water leaks assessment is a crucial aspect for the management of the water distribution systems. One strategy commonly used for the leakage reduction is to control the network pressure. Many studies have been dedicated to both the definition of the law between the leaks flow rate and the network pressure and the parameters that influencing the phenomenon. This paper presents the preliminary results of an experimental research on the water leaks evaluation conducted at the Laboratory of Hydraulics and Maritime Construction at the Università Politecnica delle Marche in Ancona, Italy. The tests were carried out varying the hydraulic operating conditions and simulating leakages from holes with different shape and size. Furthermore, different pipe materials were considered. The first results of the laboratory experiments show that the leakage from the hole increases as the pressure in the pipeline increases. The coefficients of the mathematical law for the leakage evaluation in function of the pressure were estimated. The results were compared with similar studies described in the literature.

Keywords
Water distribution systems, leakage-pressure relationship, experimental setup.

1 INTRODUCTION

The leakage reduction in water distribution systems (WDSs) is a fundamental aspect for water utilities as it is one of the macro-indicators of the technical conditions for providing the service. Leakage reduction requires the identification of the parameters that most influence the amount of volume lost and the definition of the relationships that describe the phenomenon, also in support of hydraulic modelling [1]. This issue has been addressed in recent years through both laboratory tests (e.g. [2]; [3]) and numerical modelling (e.g. [4]). The equation that generally describes the flow rate Q exiting a hole as the pressure P varies is:

$$Q = aP^b \tag{1}$$

where a and b are the coefficient and exponent respectively in the loss model. The values of the exponent b derived from experiments and field studies are between 0.5 and 2.79 (e.g. [5]). Factors influencing the value of b include the material, type of rupture, soil characteristics, flow rate and nature of the phenomenon. Recent studies have shown that the area of the leakage opening A_f (e.g. longitudinal or circular holes or cracks) increases linearly with the pressure value, for different materials and different loading conditions (e.g. [4]). The relationship linking the change in hole area to leakage flow is linear when the behaviour of the material constituting the pipe is of the elastic type. De Marchis and Milici [6] investigate the effectiveness of the suggested formulations by different authors finding that in the absence of leak area deformation, the exponent b of (1) is 0.51 and the discharge coefficient a linearly increases as the leak area grows and the slope of the linear trend is higher for circular leak than for transverse cracks. For elastic-plastic or viscoelastic behaviour, on the other hand, it is necessary to introduce other formulations. Several studies have analysed the behaviour of the leakage hole area depending on the pressure value and have proposed further modifications to introduce and quantify new aspects (e.g. [7] and [8]).

In this paper, the results of an extensive series of experimental tests in which a water leak in a pressurised system was simulated are analysed; the tests were conducted under varying system operating conditions, flow rate and pressure, and hole shape and size.

A first series of experiments was conducted on a PVC DN110 PN16 pipe by simulating leakage with the insertion of a tap on top of which metal nozzles with holes of different shapes and sizes were placed.

For a more realistic representation of leakage, the setup was recently modified to start a second series of experiments on a cast-iron pipe DN100 PN16 where a 2 mm diameter circular hole was drilled in the pipe wall.

2 EXPERIMENTAL SETUP

The experimental research for the evaluation of water loss under varying hydraulic operating conditions and hole geometry was conducted at the Laboratory of Hydraulics and Maritime Construction at the Università Politecnica delle Marche in Ancona, Italy.

2.1 Original setup

A pressurised hydraulic system consisting of DN110 PN16 PVC pipes with a total length of 20m was recently built in this facility, into which a DN100 spheroidal cast-iron pipeline with a length of 6m was inserted (see Figure 1). The circuit is fed by a 3m^3 free surface tank, while the flow rate and pressure conditions are guaranteed by a Caprari CVX321/3 5.5kW vertical multistage radial impeller pump with a nominal frequency of 50Hz. During operation the flow rate and operating head are 7.5l/s and 45.98m respectively, the minimum flow rate is 4l/s at a head of 56.93m while the maximum flow rate is 10.2l/s at a head of 32.57m. The electric pump is equipped with a three-phase inverter that allows the number of motor revolutions to be varied in terms of frequency from 35Hz to 50Hz, while a spheroidal cast-iron DN100 and PN16 flow valve with a parabolic shutter is installed at the end of the circuit, before the outlet into the discharge tank. This equipment makes it possible to regulate the operation of the system in different pressure and flow terms. The overall layout of the system is shown in Figure 1.

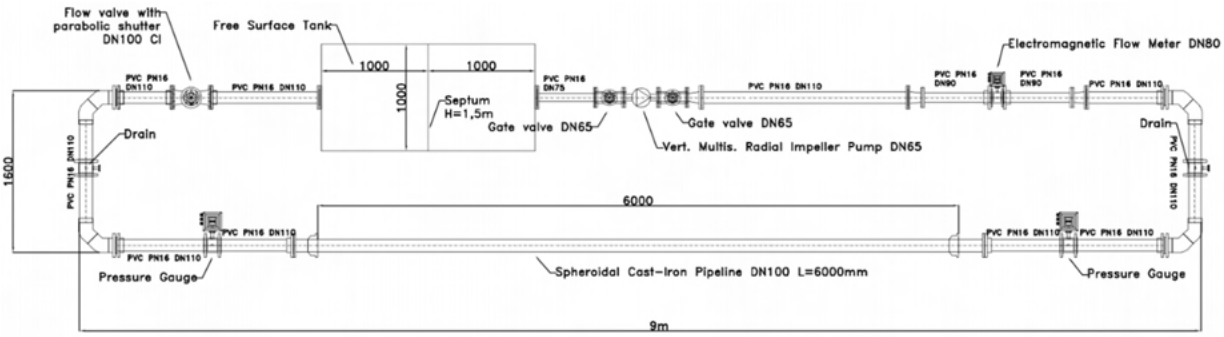

Figure 1. Layout plan of the hydraulic circuit installed at the Hydraulics and Maritime Construction Laboratory of the Università Politecnica delle Marche in Ancona

Operating conditions are measured by an electromagnetic flow meter E-H Promag 10D80 in the range (0-10.5)l/s with an accuracy of +/-0.5% of the reading and by two diaphragm pressure gauges in the range (0-1)MPa with an accuracy of +/-0.3% of the reading. There are several screwed branches in the system for the insertion of measuring instruments or drain cocks.

The simulation of the leakage was realised by inserting a ball valve and a short DN20 drain pipe closed at the end by a removable cap on which a series of metal discs with holes of different size and geometric shape were inserted into the PVC section of the circuit. The discs, 2mm thick, were drilled with a laser cutting machine with an accuracy of ± 0.1mm. Circular and rectangular holes of different sizes were used in the tests performed, the overall picture of which is shown in Figure 2 and Table 1. The dimensions of the holes were defined considering the following elements: (i) the outgoing flow rate did not exceed 50% of that circulating in the system; (ii) the maximum size of the hole was compatible with the internal diameter of the drain plug. For rectangular holes, different combinations of dimensions were also considered, but with the same area.

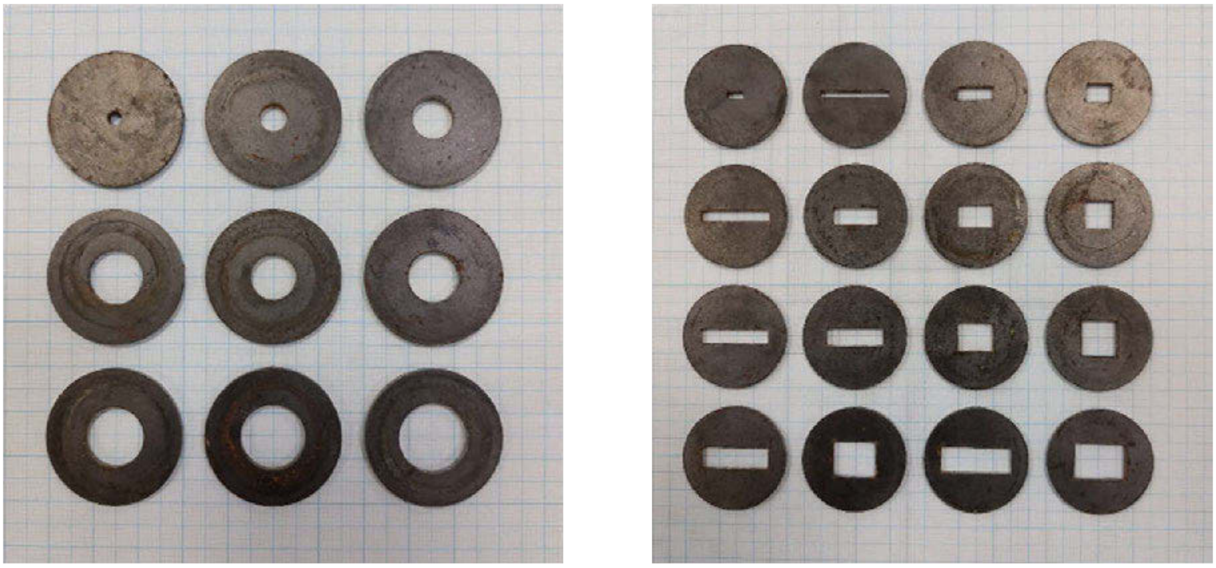

Figure 2. Nozzles used in the tests simulating leakages of different size and shape

Table 1. Characteristic dimensions of the holes simulating the leakage subject of the experimental analysis. The subscripts "f" and "i" refer to the hole and the pipe of the system respectively

Circular holes			**Rectangular holes**									
D_f	A_f	A_f/A_i	B	L	A_f	A_f/A_i	L/B	B	L	A_f	A_f/A_i	L/B
[mm]	[mm^2]	[-]	[mm]	[mm]	[mm^2]	[-]	[-]	[mm]	[mm]	[mm^2]	[-]	[-]
3	7.069	0.00096	2.00	5.00	10.00	0.00136	2.50	4.05	20.00	81.00	0.01101	4.94
6	28.274	0.00384	1.80	20.00	36.00	0.00489	11.11	5.00	16.20	81.00	0.01101	3.24
9	63.617	0.00864	3.60	10.00	36.00	0.00489	2.78	8.10	10.00	81.00	0.01101	1.23
10	78.540	0.01067	5.00	7.20	36.00	0.00489	1.44	10.00	10.00	100.00	0.01359	1.00
11	95.033	0.01291	3.20	20.00	64.00	0.00870	6.25	6.05	20.00	121.00	0.01644	3.31
12	113.097	0.01537	5.00	12.80	64.00	0.00870	2.56	10.00	12.10	121.00	0.01644	1.21
13	132.732	0.01804	6.40	10.00	64.00	0.00870	1.56	7.20	20.00	144.00	0.01957	2.78
14	153.938	0.02092	8.00	8.00	64.00	0.00870	1.00	10.00	14.40	144.00	0.01957	1.44
15	176.715	0.02401										

Tests were performed for each hole by varying the frequency of the pump using the inverter (35Hz, 40Hz, 45Hz, 50Hz) and repeating each test twice on each disc, for a total of 8 tests per hole. The test consists of opening the tap for 60s and measuring the volume exiting the bore and collected in a tank below the system. Pressure and flow rate changes during the tests are made by keeping the valve opening constant when the flow is started and varying the pump speed.

2.2 Modified setup

The objective of the hydraulic circuit modification was to reproduce in the laboratory experimental conditions as close as possible to the pipe breaks under real conditions, i.e. drilling a circular hole in the experimental pipe (see Figure 3). Given this premise, the design of a new plant part with modifications of the existing system was considered.

To have a water flow from the cast-iron pipe hole without the insertion of metal plugs and taps, a bypass pipe must be added where the water circulates normally without affecting the test pipe. The water that normally flows in the PVC pipe, called the bypass pipe, is moved to the cast-iron pipe, where the break is located 80cm above the level of the existing system. This is achieved by the use of 3 motorized valves powered by an electrical panel, 2 PVC tees, 2 PVC 90° bends and the flanged inlet and flanged cup fittings. The latter two special elements are required for the connection between cast-iron pipe (test pipe) and PVC pipes; specifically, upstream a flanged spheroidal cast-iron inlet with a nominal diameter of DN110 and PN16 was used, while downstream a flanged cup with a DN110 and PN16 spheroidal cast-iron joint was used. A view of the system layout after these modifications is illustrated in Figure 3.

The tests were carried out with four frequency values: 35Hz, 40Hz, 45Hz, 50Hz. This was possible by acting on the three-phase inverter connected to the system's electric pump, modifying the number of revolutions per second of the motor. Three tests were carried out for each frequency value in order to assess the repeatability conditions of the measurement, thus making a total of 12 tests. The parameters that were varied by varying the number of revolutions of the pump were the pressure and the operating flow rate of the system. As the opening and closure stages of the motorized valves take place in 9s, the full opening of the valves corresponds to the start for the measurement. The time interval chosen for the measure is always 60s, in order to have a sufficiently stable condition of the measurement unaffected by the transient phase of the start-up of the flow in the pipeline. Thus, the total duration of the test by considering the valve operating times of both opening and closure is 78s.

Figure 3. View of the hydraulic system after modifications; particular of the cast-iron pipe with hole used in the experiments (box on the right)

3 RESULTS

3.1 Original setup

For each test, the pressure and flow rate in the pipeline were measured, as well as the volume of water leaking out of the hole; the leakage, expressed in terms of flow rate, was obtained by dividing the volume collected by the duration of the test. The results obtained were processed to establish primarily the relationship existing between the operating pressure in the pipeline and the leakage. Secondly, an attempt was made to analyse the role played by the size and shape of the hole on the leakage itself.

The main results of the experimental tests are shown in Figure 4, where the measurement in l/s of the flow rate exiting the hole as the pressure in the pipeline varies, expressed in metres of equivalent water column, is represented for both rectangular holes (left panel) and circular holes (right panel). It can be observed that the tendency for the leakage to increase as the pressure in the duct increases is confirmed, as evidenced both under experimental (e.g. [2]) and real-life conditions. From a quantitative point of view, the operating pressures vary in the range (150÷415)kPa to which corresponds an output flow rate in the range (0.1÷2.4)l/s equivalent to a loss between 1.5% and 23% of the system flow rate.

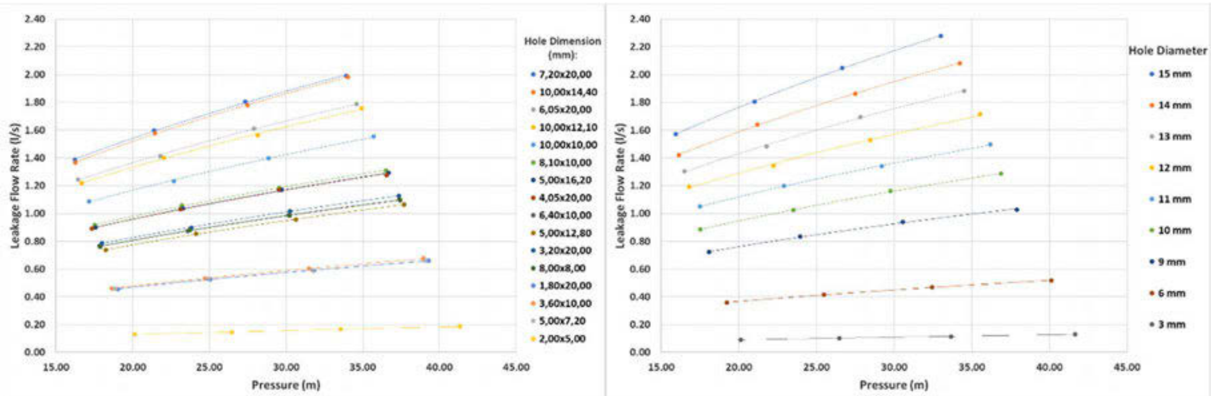

Figure 4. Variation of loss as a function of pressure for rectangular (left) and circular (right) holes.

Comparing the results obtained for rectangular and circular holes, there are no significant differences in behaviour for the two types. The greatest values in terms of measured leakage for circular holes are due to the maximum values of the circular section areas being larger than the rectangular ones. In both cases, it can be seen that the outlet flow rate has a steeper rise than the pressure as the hole area increases. Furthermore, increasing the frequency of the pump motor results in a corresponding increase in pressure, which is lower the larger the area of the hole.

As far as the influence of the hole shape on leakage is concerned, the test results do not show unambiguous behaviour. In fact, if for holes with an area greater than 100mm^2 it is observed that the leakage is greater for the holes with the largest L/B ratio, i.e. those with a more elongated shape, the same thing does not occur for holes with a smaller area where the greatest flow rate at the same area is for L/B values smaller than the maximum value.

Applying the model represented by equation (1) to the results of the experimental tests, we obtain the results shown in Figure 5 in which the average value of the coefficient a (in red) and the exponent b (in blue) are represented for each of the tests on a given hole and with an assigned frequency. The coefficient a increases as the ratio A_f/A_i increases, where A_f is the area of the hole and A_i is the internal area of the pipe, with a monomial law that deviates slightly from the linear trend line. The behaviour is essentially similar for rectangular and circular holes, the exponent of the function being 0.94 and 0.92 respectively, with a tendency for the interpolating function to overestimate the value of a as A_f/A_i increases. As regards the coefficient b, the experimental results show that the value is essentially constant for all the tests performed, with an average value of about 0.5. In this case, there is no significant difference for the two types of holes, the difference between the two coefficients being 1‰ and the standard deviation of the values of all the tests, both rectangular and circular, being of the order of 1%.

The results obtained are in good agreement with the experimental study by De Paola and Giugni [2] regarding the tests on steel pipes, under the same conditions analysed (constant pressure tests). In particular, it is observed that: (i) the exponent *b* of (1) is substantially coincident in the two studies for both rectangular and circular holes, with slightly higher average values for the tests on steel pipeline; (ii) the coefficient *a* of (1) is in agreement for values of the A_f/A_i ratio < 0.01 while for larger values the experimentation in metal pipeline presents larger values of a for both types of holes.

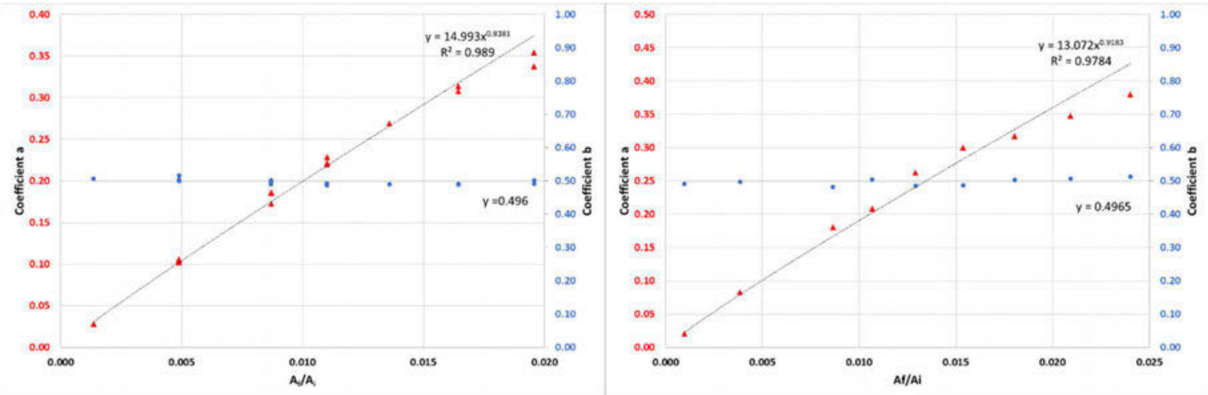

Figure 5. Values of coefficients a (in red) and b (in blue) for rectangular (left) and circular (right) holes

More tests with rectangular holes will be executed changing both the area and the shape of the hole in order to analyse the influence of some parameters as the A_f/A_i ratio or the L/B ratio on the relationship between the pressure and the leakage flow rate.

3.2 Modified setup

The preliminary results were obtained by measuring the leakages from a drilled circular hole of 2mm. They were elaborated to establish the relationship existing between the operating pressure in the pipeline and the leakage (1).

The relationship between the leakage and the average pressure is shown in Figure 6. It can be observed that the tendency for the leakage to increase as the pressure in the pipeline increases is confirmed. Furthermore, it can be seen that the increase of the frequency of the pump motor leads to a corresponding increase in the pipe pressure with an increase in the flow rate from the hole.

In order to compare the results of these preliminary tests with those obtained in the original setup for circular holes of smaller diameter, i.e. 3mm, the coefficients *a* and *b* were computed by equation (1) and by the law of the curve interpolating the experimental values of Figure 3b:

$$a = 13.072\left(A_f/A_i\right)^{0.9185} \tag{2}$$

By using the equation (1) the coefficient *a* obtained in the new test is 0.052 and it is larger than the value of 0.0205 obtained with the 3mm hole test of original setup; while the coefficient *b* of the new test is 0.422 and it is smaller than the value 0.4916 obtained in the previous tests.

By the equation (2), the coefficient *a* for the original setup with A_f/A_i=0.00096 is 0.023 and for the modified setup with a ratio A_f/A_i=0.0004 is 0.0099. Instead, the coefficient *b* is constant and equal to 0.4965.

Therefore, the value of coefficient *b* is smaller than results obtained in the previous experimental investigation, while the coefficient *a* is larger than the value obtained in a DN110 and PN16 PVC pipe with a hole with a larger diameter of 3 mm. Thus, the *a*-values obtained for a 2mm diameter hole deviate from the trend for larger diameter holes, where *a* decreases as the diameter decreases.

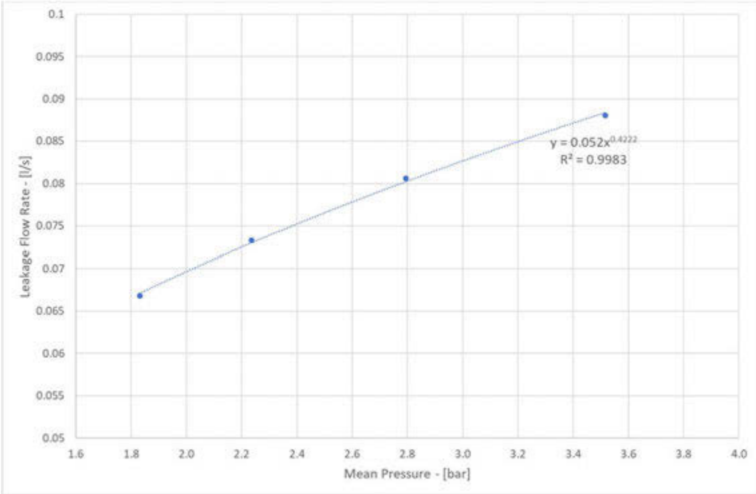

Figure 6. Average leakage as a function of the average pressure in the pipeline in the minute before the test. Equation (1) with the coefficients a and b and the associated error R^2 is shown

This difference could be justified by the fact that the leakage in the original setup referred to a PVC pipe, whereas in the present case the test is made on a cast-iron pipe. Moreover, in the original setup the leak was simulated by installing a junction with an interception spherical valve at the end of which there was a nozzle with the hole, while in this case the water can flow out of the hole with no constraints.

Further tests will be developed with different hole diameters and the results will be compared with the experimental values previously obtained for the PVC pipe and with tests available in the literature.

4 CONCLUSIONS

At the Hydraulics and Maritime Construction Laboratory of the Università Politecnica delle Marche, an experimental investigation was carried out in which a water leak in a pressurised system was simulated by varying the operating conditions of the system, flow rate and pressure, and the shape and size of the holes.

The first series of experiments shows that the leakage from the hole increases as the pressure in the pipeline increases. These results are in agreement with similar studies described in the literature. Comparing the results between similar experiments (e.g. [2]) it can be noted that: (i) the leakage in the metallic pipe is greater than that in the PVC one; (ii) differences in equations (1) are negligible for smaller size holes. Moreover, the preliminary results of the analysis of the influence of the hole shape on the leakage show a different behavior between holes with area greater than 100mm^2 and those with a smaller one, being the leakage greater for the holes with the largest L/B ratio in the first case and the opposite for those with smaller area. The value obtained for *b* coefficient is constant and it is very close to value of 0.5, typical of the Torricelli's law (e.g. [6]).

The experiments applied to the cast-iron pipe with a drilled hole confirmed the tendency for the leakage to increase as the pressure in the pipeline increases. The coefficients of equation (1) calculated for this set of tests are greater for the *a* coefficient and smaller for the *b* one with respect to those of the PVC pipe respectively. This preliminary result could confirm the hypothesis of De Paola and Giugni [2] that the leakage is greater in the metallic pipe.

A new set of tests will be executed to support and to generalize the model of the leakage flow rate prediction as a function of the pressure.

5 REFERENCES

[1] G. Darvini, V. Ruzza, and P. Salandin, “Performance Assessment of Water Distribution Systems Subject to Leakage and Temporal Variability of Water Demand”, Journal of Water Resources Planning and Management, 146(1), 2020.

[2] F. De Paola and M. Giugni, “Leakages and pressure relation: an experimental research”, Drink. Water Eng. Sci., 5, 2012, pp. 59-65.

[3] M. De Marchis, C.M. Fontanazza, G. Freni, V. Notaro and V. Puleo, “Experimental Evidence of Leaks in Elastic Pipes”, Water Resources Management, 30, 2016, pp. 2005-2019.

[4] A.M. Cassa, J.E. Van Zyl and R.F. Laubscher, “A numerical investigation into the effect of pressure on holes and cracks in water supply pipes”, Urban Water Journal, 7, 2010, pp. 109-120.

[5] A.M. Cassa and J.E. Van Zyl, “Predicting the leakage exponents of elastically deforming cracks in pipes”, Procedia Engineering, 70, 2014, pp. 302-310.

[6] M. De Marchis and B. Milici, “Leakage estimation in water distribution network: effect of the shape and size cracks”, Water Resources Management, 33, 2019, pp. 1167–1183.

[7] M. Franchini and L. Lanza, “Leakages in pipes: generalizing Torricelli's equation to deal with different elastic materials, diameters and orifice shape and dimensions”, Urban Water Journal, 11(8), 2014, pp. 678-695.

[8] J.E. Van Zyl, A.O. Lambert and R. Collins, “Realistic modeling of leakage and intrusion flows through leak openings in pipes”, Journal of Hydraulic Engineering, 143(9), 2017, pp. 1-7.