Experimental study of water losses through a circular leakage hole in PVC pipes

A Hotupan1, A Hădărean2

1 Technical University of Cluj-Napoca, Building Services Faculty, Department of Building Services Engineering, 21 Decembrie 1989 Boulevard 128-130, 400604 Cluj-Napoca, Romania
2 Technical University of Cluj-Napoca, Building Services Faculty, Department of Building Services Engineering, 21 Decembrie 1989 Boulevard 128-130, 400604 Cluj-Napoca, Romania

Corresponding author: adriana.hadarean@insta.utcluj.ro

Abstract. The water loss is a phenomenon which attends the water supply system on its operating lifetime and it represents the difference between the water volume measured at the input of a water distribution network and the water volume billed to the end-users. The water loss reduction is an important topic for the water supplying companies and the knowledge of the real water volumes lost from a supply system is an essential element in water balance. The water losses may be classified in “real losses” and “apparent losses”: the apparent losses cannot be quantified, but the real losses can be estimated by calculus. The complexity of this phenomenon lies in the fact that this water losses can’t be calculated with a single equation, generally valid for each real situation. The equations mentioned in the technical literature can be applied to a specific situation. This paper presents an experimental study of the variation of the hydraulic parameters in a PVC water flow pipe in two cases: 1. normal operation and 2. leak simulation, when a circular hole is drilled into a PVC pipe. Furthermore, the results of this study are discussed and analysed in order to calculate the value of the leakage exponent $N_1$.

1. Introduction

Water losses in supply water systems, as a major factor in the worldwide water management, can occur all over the system. Water losses can be located at: water intake section, water treatment plant, pumping station, storage tank and supply and distribution network pipes.

The most common water losses came from leaking joints and in this case the volume of water loss is quite small and difficult to track down. However, the impact of high water pressure and the effect of the ageing of pipe material increase the chances of pipes to burst. Therefore, in time cracks can occur along or across pipeline as circular holes or hairline configurations. The water volumes lost in this case are significant and they have an important impact on the operational management and on the economic management of water system, e.g. water balance [1].

The type of the pipe material represents a major factor in the operation of the water system, because in the case of high water pressure the fluid and the pipe works like an assembly. Hence, the pipe wall can absorb the stress grace to the material ability of deformation (expansion and resilience to initial diameter) when pressure drops. From this point of view, the flexible pipes have a significant advantage.
versus the rigid pipes, but repetitive deformation of the material may lead to the ageing of the material pipe. On the other hand, the rigid pipes have strong pipe wall and joints to withstand most of the anticipated loads, thus a longer operating lifetime. The major disadvantage of the rigid pipes is the corrosion that in time will perforate the wall pipe. Based on the different performance under dynamic water pressure of these types of pipe a separate analysis of the water leakage it will be mandatory.

The water leakage originating from a burst pipe can be assimilated to the water flow rate into an orifice which is regulated by the well-known equation [2], [3]:

\[ Q_{RL} = C_d \cdot a \cdot \sqrt{2 \cdot g \cdot h} \]  

(1)

where: \( Q_{RL} \) is discharge flow, m\(^3\)/s;  
\( a \) - area of the leak hole, m\(^2\);  
\( g \) - gravitational acceleration, m/s\(^2\);  
\( C_d \) - discharge coefficient (dimensionless);  
\( h \) - pressure in the axis hole, mH\(_2\)O.

The values of the coefficient \( C_d \) depend on the orifice shape and dimension, the position of hole on the wall pipe and on the Reynolds number [4], [10]. The \( C_d \) values increase along with the Re number up to turbulent roughness flow zone thereafter the values remain constant, usually ranging from 0.57 to 0.85 [9], [23]. For a given situation the \( C_d \) values can be taken from the technical literature in analytical or graphical form [6], [8].

Equation (1) emphasizes the dependence of the leakage on the water pressure, but it has been proved that it cannot be properly reliable for different types of pipe materials [18], [19]. To overcome this problem, scientific literature offers alternative pressure-leakage relationships. The most general expression used especially in hydraulic network modelling is [20], [21], [3], [22]:

\[ Q_{RL} = C \cdot H^{N_1} \]  

(2)

In other experimental and numerical studies on PVC pipe [15], [16], [17] the equation used for determination of the discharge flow through circular orifices is:

\[ Q_{RL} = C_d \cdot a \cdot \sqrt{2 \cdot g \cdot H^{0.5}} \]  

(3)

where: \( H \) is the pressure measured in the orifice axis in mH\(_2\)O;

In this paper an alternative approach is used to obtain the relationship between pressure-leakage flow, based on the equations (1) and (2):

\[ Q_{RL} = C_d \cdot a \cdot \sqrt{2 \cdot g \cdot H^{N_1}} \]  

(4)

where \( N_1 \) is leakage exponent, usually set between 0.5 and 2.79 [5], [11], [23]. These values are influenced by the type of the orifice, the thickness of the pipe wall, the pipe elastic modulus and Reynolds flow regimes [6]. Therefore, these uncertainties affect the estimation of the exponent \( N_1 \) and the outflowing flow through the hole, too.

In the equation (3) the value of the coefficient \( C_d \) can be considered as known, because its value increases almost linearly with the area of the hole and moreover its values are given by the scientific literature. Much more uncertainty it is given by the estimation of \( N_1 \) due to the large range values. Additional, the increasing adoption of the plastic pipes in the water supplies systems together with the accessibility of material and technologies for pipe production call for an accurate hydraulic characterization of a possible generation of orifices.

In this context, the aim of this paper is to obtain experimental values for the leakage exponent \( N_1 \) for a circular leakage holes in PVC pipes.

2. Materials and Methods

2.1. Experimental apparatus
The experimental setup used for this study includes two parts as shown in figures 1 and 2:
- the hydraulic bench composed of a water tank of 165 liters, a variable speed pump and a flow control gate (figure 1);
- the mobile bench which is an vertical mounted aluminium board with different types of pipes in terms of diameters and roughness (figure 2).

This experimental bench was built in order to measure the leakage volumes thorough a circular hole drilled in the wall of a PVC pipe and in the same time to study the relationship between the water flows rate and the water pressure in PVC pipes.

The parts of the experimental bench are: the 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 $D=27.2\text{mm}$ (6) and three pressure sensors SPDA1, SPDA2 and SPDB1.

The physical bench didn’t have got a water circulating system. Hence, the water tank was used as water supply source via pump unit to ensure the continuous flow of water and the leak will be discharged into a small tank. By using both the flow control gate and the variable speed pump, various pressures and flow rates of the water were obtained during this experiment. A flowmeter with 5% accuracy was installed to measure the pipe flow rate. Also, three pressure sensors (SPDA1, SPDA2, and SPDB1) with a range of 6 bar and 5% accuracy were installed on the pipe to measure the water pressure. These three sensors and the flowmeter are connected to a data acquisition soft. To simulate a leak on the PVC pipe a circular orifice of 2.6 mm diameter was drilled in the pipe. Into this hole a connection hose is placed to allow a small size plastic pipe and the SPDA2 sensor to be used. The role of the small size pipe was to ensure a way to collect and transport the water leaks into the small tank. The water circulation through this small pipe is controlled by an on/off valve placed backward the leakage hole on the reverse side of the aluminium board. This type of valve has the advantage of great tightness when closed and a low flow resistance in the open position.

2.2. Experimental procedures and data processing
The measurements were conducted on the pipe situated on the 5 position of the aluminium board (see figure 2), the pipe material is PVC of 32 x 2.4 mm with an inside diameter of $D =27.2\text{mm}$. As shown in figure 2 the flowmeter is located on the upstream supply pipe, so during the experiment all the ball valves were closed except the one placed on the PVC pipe. In this manner the entire water flow will be directed to this pipe.

The pressure sensors SPDA1 and SPDB1 placed on the studied pipe (see figure 2) will indicate the pressure values at the upstream and downstream of the circular hole. The SPDA2 sensor will measure the pressure in the drilled hole.

The hydraulic parameters (pressure and flow) data in the physical model were captured on SACED – Edibon software (see figure 3).
Throughout each test, the pressure and the upstream and the downstream flow rates were measured, in order to estimate the water loss through a circular hole. For that purpose the following steps were conducted:

**Step 1:** with the control flow gate (7) fully opened:
- the ball valve on the PVC pipe is opened and the rest of the ball pipes are closed;
- the pump is started;
- the water flowrate is set to 20 l/min on the PVC pipe:
  1. normal operation: the on/off valve is set to closed position. The water pressure values in the pipe are acquired by the sensors SPDA1 and SPDB1 (see table 1).
  2. leak simulation: the on/off valve is set to open position for 30 seconds. In this period of time the outgoing flow through the orifice ($V_{RL}$) via the small plastic pipe was collected into a small tank and the water pressure was measured with SPDA1, SPDA2 and SPDB1 pressure sensors. The collected water was measured with a graduate recipient.

The above operations were repeated with an increase of the flowrate of 2 l/min for each experiment up to the value of 38 l/min. The collected data are presented in table 1.

### Table 1. Measured values (Step 1)

| Test ID | $Q$ (l/min) | $SPDA_{1}$ (cmH$_2$O) | $SPDB_{2}$ (cmH$_2$O) | $SPDA_{1}$ (cmH$_2$O) | $SPDA_{2}$ (cmH$_2$O) | $SPDB_{2}$ (cmH$_2$O) | $t$ (sec) | $V_{RL}$ (cm$^3$) |
|---------|-------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------|-----------------|
| 1       | 20          | 84                  | 82                  | 81                  | 10                  | 80                  | 30      | 138             |
| 2       | 22          | 110                 | 108                 | 106                 | 12                  | 105                 | 30      | 163             |
| 3       | 24          | 140                 | 137                 | 135                 | 15                  | 133                 | 30      | 188             |
| 4       | 26          | 173                 | 169                 | 166                 | 17                  | 163                 | 30      | 210             |
| 5       | 28          | 208                 | 203                 | 199                 | 19                  | 195                 | 30      | 233             |
| 6       | 30          | 247                 | 241                 | 239                 | 22                  | 234                 | 30      | 260             |
| 7       | 32          | 288                 | 280                 | 278                 | 24                  | 272                 | 30      | 282             |
| 8       | 34          | 329                 | 320                 | 318                 | 26                  | 311                 | 30      | 300             |
| 9       | 36          | 379                 | 369                 | 368                 | 29                  | 359                 | 30      | 328             |
| 10      | 38          | 427                 | 416                 | 414                 | 32                  | 404                 | 30      | 343             |

To emphasize the major influence of the pressure on the leakage the steps 2 and 3 are mandatory. In these two cases the operating pressure was amplified by partially closing the flow control gate (7).

**Step 2:** with the control flow gate (7) partially closed (5 rotations) all the operations described at the step 1 were repeated and the measured values are indicated in table 2.
Table 2. Measured values (Step 2)

| Test ID | Measured values with on/off valve | Measured values with on/off valve |
|---------|----------------------------------|----------------------------------|
|         | (l/min) SPDA1 (cmH₂O) SPDB2 (cmH₂O) | (l/min) SPDA1 (cmH₂O) SPDB2 (cmH₂O) |
| 1       | 20     115 116 | 106 14 107 30 159 |
| 2       | 22     165 164 | 158 18 157 30 195 |
| 3       | 24     191 190 | 182 20 181 30 210 |
| 4       | 26     239 236 | 231 23 228 30 245 |
| 5       | 28     326 321 | 320 30 315 30 287 |
| 6       | 30     379 373 | 367 32 361 30 310 |
| 7       | 32     432 425 | 418 35 411 30 341 |
| 8       | 34     492 484 | 477 39 469 30 364 |
| 9       | 36     577 567 | 551 43 541 30 396 |
| 10      | 38     639 629 | 622 49 612 30 423 |

Step 3: with the control flow gate (7) partially closed (10 rotations) the same procedure as describe at the step 1 was applied and the measured values are indicated in table 3.

Table 3. Measured values (Step 3)

| Test ID | Measured values with on/off valve | Measured values with on/off valve |
|---------|----------------------------------|----------------------------------|
|         | (l/min) SPDA1 (cmH₂O) SPDB2 (cmH₂O) | (l/min) SPDA1 (cmH₂O) SPDB2 (cmH₂O) |
| 1       | 20     144 143 | 137 19 136 30 182 |
| 2       | 22     180 179 | 172 22 171 30 202 |
| 3       | 24     233 230 | 222 26 220 30 240 |
| 4       | 26     287 283 | 267 29 264 30 270 |
| 5       | 28     324 320 | 313 32 309 30 288 |
| 6       | 30     379 373 | 365 34 360 30 314 |
| 7       | 32     435 428 | 423 37 417 30 341 |
| 8       | 34     495 487 | 481 41 474 30 362 |
| 9       | 36     562 553 | 547 45 538 30 392 |
| 10      | 38     639 629 | 622 49 612 30 423 |

Once the data acquisition were gathered, the next step was to calculate the leakage exponent $N_1$ based on the experimental data. This aspect involves the following calculation:

- Water velocity values for PVC pipe of D diameter, by using the following equation [2], [4]:
  \[ V = \frac{4Q}{\pi D^2} \] (5)

- Reynolds number by applying the formula:
  \[ Re = \frac{V\cdot D}{\theta} \] (6)

where: $V$ is average velocity across the pipe section, m/s;
$\theta$ - kinematic viscosity of the fluid, m²/s. Its value vary with the temperature, so in this case the value of $\theta = 1.01\cdot10^{-6}$ m²/s was used [7];
$D$ - inside diameter of the pipe, m.

and then, based on the Reynold number, the water flow regime was established.
- Leakage exponent $N_1$ of the hole with the relation:
\[ N_1 = \log H \cdot \left( \frac{Q_{RL}}{c_d a \sqrt{2g}} \right) \]  

(7)

where: \( H \) is the value indicated by the SPDA2 sensor in mH\(_2\)O;

\( a \) – area of the circular orifice with the diameter of \( d = 0.0026 \) m obtained with:

\[ a = \pi d^2 \]  

(8)

The discharge water flow in the hole, \( Q_{RL} \), it can be calculated with the equation [7]:

\[ Q_{RL} = \frac{V_{RL}}{t} \]  

(9)

where \( V_{RL} \) is the leakage volume measured during a period of time of \( t = 30 \) sec.

The value of coefficient \( C_d \), in this case, corresponds to the diameter ratio: \( d/D = 0.095 \) namely \( C_d = 0.78 \) [6], [8].

The \( N_1 \) leakage exponent values obtained based on the experimental data with the use of the above equations are presented in the table 4.

### Table 4. \( N_1 \) leakage exponent calculated values

| ID | \( Q \) (l/min) | \( V \) (m/s) | Re | Water regime flow | \( Q_{RL} \) (l/min) | \( N_1 \) | \( Q_{RL} \) (l/min) | \( N_1 \) | \( Q_{RL} \) (l/min) | \( N_1 \) | \( N_1 \) |
|----|----------------|-------------|----|------------------|---------------------|-------|---------------------|-------|---------------------|-------|-------|
| 1  | 20             | 0.57        | 11917 | turbulent        | 0.28                | 0.601 | 0.32                | 0.631 | 0.36                | 0.666 |
| 2  | 22             | 0.63        | 13109 | turbulent        | 0.33                | 0.574 | 0.39                | 0.605 | 0.40                | 0.662 |
| 3  | 24             | 0.69        | 14300 | turbulent        | 0.38                | 0.546 | 0.42                | 0.598 | 0.48                | 0.616 |
| 4  | 26             | 0.75        | 15492 | turbulent        | 0.42                | 0.525 | 0.49                | 0.550 | 0.54                | 0.575 |
| 5  | 28             | 0.80        | 16684 | turbulent        | 0.47                | 0.517 | 0.52                | 0.551 | 0.58                | 0.568 |
| 6  | 30             | 0.86        | 17876 | turbulent        | 0.52                | 0.480 | 0.57                | 0.540 | 0.63                | 0.520 |
| 7  | 32             | 0.92        | 19067 | turbulent        | 0.56                | 0.468 | 0.62                | 0.503 | 0.68                | 0.481 |
| 8  | 34             | 0.98        | 20259 | turbulent        | 0.60                | 0.450 | 0.68                | 0.455 | 0.72                | 0.469 |
| 9  | 36             | 1.03        | 21451 | turbulent        | 0.66                | 0.418 | 0.73                | 0.438 | 0.78                | 0.424 |
| 10 | 38             | 1.09        | 22642 | turbulent        | 0.69                | 0.414 | 0.79                | 0.389 | 0.85                | 0.368 |

Average values | 0.499 | 0.526 | 0.535 |

2.3. Synthesis of the Experimental Results

According to the experimental and analytical results the following aspects can be drawn:

- **Pressure variation along the PVC pipe**

The values from the tables 1, 2 and 3 together with the graphical representation captured during this experimental study (see figure 4) show that when an crack appear in the pipe wall (the on/off valve set on open position) the fluid pressure suddenly drop dawn. In addition, for a constant flow rate, the gap between the fluid pressure for the open and close position of the on/off valve increases when the operating pressure increases too.
7

The average value obtained for the exponent $N_1$ based on the experimental data (0.499, 0.526 and 0.535) are very close to the value mentioned in other experimental studies ($N_1= 0.5$) for PVC pipes (see equation (3)) [12], [13]. So, by using this value a good estimation of the water loss in a hole can be obtained in the case of water turbulent regime flow.

- **Water loss in the orifice**
  
  The water loss in the orifice depends on the dimension of the hole and on the water flow rate transported by the PVC pipe, in the same time, as shown in figure 5. So, increase values of the water flow rate will lead to increase quantities of water loss in the hole as shown in the table 4 and figure 5. Moreover, as one can be seen in figure 6, the water loss in the orifice depends also on the orifice axis pressure in the PVC pipe.

![Figure 4. Pressure variation in PVC pipe during the experiment study](image)

- **Leakage exponent $N_1$ variation in the orifice**

  ![Figure 5. Water loss in the orifice in ratio with the water flow rate in the PVC pipe](image)

  ![Figure 6. Water loss in the orifice in ratio with the orifice axis pressure](image)
3. Conclusions

Nowadays, the major concern of the worldwide water supplies services and management is to find a way to control, prevent and reduce the water losses. In this context, the aim of the paper was to present indicators that once used in the real water distribution networks may lead to the prevention of a possible failure and therefore to prevent great quantities of water to be lost.

Thus, based on experimentally data and numerical calculus and analysis, the following conclusions can be drawn:

- the presence of an orifice in the pipe wall will lead to a dropdown of the pressure in that section. This dropping in pressure was detected by the sensors SPDA1 and SPDB1 on the PVC pipe, upstream and downstream of the orifice and the sensor SPDA2 in the axis hole as shown in tables 1, 2, 3 and 4; certainly the maximum pressure drop was registered in the axis orifice.
- the value of 0.5 for leakage exponent \( N_l \) for PVC pipes and rigid pipes mentioned in the scientific literature is also confirmed by this experimental study;
- the almost linear variation of the flow rate and operating pressure in the pipe with the water losses is the orifice. This study confirmed that an increase of the flow rate and operating pressure will be followed by an increase of the water losses in the hole.

In conclusion, in order to prevent the water losses in water distribution networks it is imperative to implement an accurate pressure monitoring system, but nevertheless it will be helpful to reduce the water pressure into the networks during the period of reduced water consumption, especially during the nightly period. In this way, great quantities of water can be saved and also it can be prevented new cracks in the network pipes.

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