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Scientific Article

Hydraulic behavior of valves used in building water supply systems

Comportamento hidráulico de registros utilizados em instalações hidráulicas prediais

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ABSTRACT

This study was developed with the objective of evaluating the steady-state hydraulic behavior of gate, ball, and pressure valves with nominal diameters of ½" and ¾", which are widely used in building water supply networks in Brazil. For this purpose, tests were performed to determine the head loss in ten different valves in four openings with five replicates. A hydraulic head loss testing apparatus was set up in a pipeline network that allowed for the control, monitoring, and acquisition of data. Mean values of the K coefficient of the minor head loss and the equivalent length were estimated for the conditions evaluated. The results were analyzed using box plots, correlation, principal components analysis, and hierarchical clustering. In general, the gate valves showed lower head loss for all the relative openings considered, while the pressure valves showed the greatest head loss. Of the clusters formed, for the second group, there was a predominance of treatments with pressure valves, which showed similarity in terms of the values of the hydraulic variables due to the geometry and construction of the valves.

Keywords: correlation analysis; hydraulic design; multivariate analysis; tubing fittings; valves.

RESUMO

Este estudo foi desenvolvido com o objetivo de avaliar o comportamento hidráulico em regime permanente de registros de gaveta, esfera e pressão com diâmetros nominais de ½" e ¾", amplamente utilizados em instalações hidráulicas prediais brasileiras. Para tanto, foram realizados testes para determinar a perda de carga em dez diferentes registros, em quatro aberturas, com cinco repetições. Foi montado um aparato hidráulico de ensaio de perda de carga em uma rede de tubulação que permitiu o controle, monitoramento e aquisição de dados. Foram estimados valores médios do coeficiente K de perda de carga localizada e de comprimento equivalente para as condições avaliadas. Os resultados foram analisados por meio de gráficos *box-plot* e análises de correlação, componentes principais e agrupamentos hierárquicos. Em geral, os registros de gaveta apresentaram menor perda de carga para todas as aberturas relativas consideradas, enquanto os registros de pressão, as maiores perdas. Dos agrupamentos formados, para o segundo grupo, houve predominância de tratamentos com registros de pressão, que apresentaram similaridade quanto aos valores das variáveis hidráulicas devido à geometria e à construção dos registros.

Palavras-chave: análise de correlação; acessórios de tubulação; análise multivariada; dimensionamento hidráulico; registros.

INTRODUCTION

According to Amaral and Amaral (2016), head loss is one of the most important phenomena in pipeline hydraulics with a great influence on flow, and can be classified as major or minor. Major head loss occurs in the linear sections, when the pressure imposed by the flow decreases gradually along the pipeline length, while minor head loss occurs in singular sections, *i.e.*, in the discontinuities of linear sections, when the fluid suffers extra turbulence in its flow.

In this context, valves are accessories that establish, control, and interrupt the flow in a pipeline. Thus, they should be chosen sensibly based on their physical characteristics, location in the network, operation, and hydraulics. In building water supply networks, valves have a great influence on minor head loss, and whether in long or short pipes, which is especially important in shorter networks (AMARAL; AMARAL, 2016), as building water supply systems. These accessories can offer significant resistance to flow, even when fully open, which means that head loss is sensitive to these elements' construction design.

Head loss in valves is influenced by flow characteristics, including variation, material ageing, pipe diameter and each type of valve's individual characteristics,

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including geometric and construction characteristics, and flow control elements. Different types of valves — *e.g.*, gate, ball, and pressure valves — are widely used in building water supply systems.

In the Brazilian technical literature, there are classic publications, especially books (AZEVEDO NETTO; FERNÁNDEZ, 2015; BAPTISTA *et al.*, 2014; BISTAFA, 2018), that reference mean coefficients for head loss in valves, mainly when fully open. Although available in the literature, according to Santos-Ruiz *et al.* (2020), these values may differ considerably from reality, and it is better to determine them. In other words, one can obtain better precision in the hydraulic design of building water supply systems with more accurate information within an application interval or even from the dependence of another hydraulic variable relative to flow. It should also be noted that the devices of each market have their constructive, geometric, and material characteristics normally used, thus, there is an intrinsic imprecision when transferring international research and technical results. Another difficulty is that, as shown by Poręba *et al.* (2018), the minor head loss in valves can be influenced by the piping material in which they are installed, as well as by the set of couplings used in the test apparatus.

From the publication of the new ABNT NBR 5626:2020 Standard (ABNT, 2020), which suggests the use of flow *vs.* pressure curves for modeling the hydraulic behavior of sanitary fixtures, numerical software as EPANET 2.2 (ROSSMAN *et al.*, 2020) can be used to model potable water building systems, and to simulate their hydraulic performance, which makes determining device head loss coefficients in operating situations, *i.e.*, when they are not fully open, valuable.

Regarding this, pressure valves are intended to control the flow, so showers, which are the least favorable sanitary fixture in terms of the pressure available in building networks (FERREIRA *et al.*, 2021), may have their operation simulated by designers for different openings if their head loss coefficient is available for this situation.

Gate and ball valves are indicated for flow blocking, but they may also be used for energy dissipation, in situations of high-pressure flow, as in low areas of public water distribution networks. Thus, the useful life of devices and connections can be preserved. However, to be accurate about this generated protection effect, it is also necessary to know their head loss behavior in different openings. Furthermore, even though they are inefficient for flow control, occasionally these devices can be used to do so.

There is also a lack of technical-scientifical works, or even manufactures information, that deal with the hydraulic behavior valves built for Brazilian market, mainly for pressure valves. International information is also scarce, even with this being crucial to the correct design of potable water building systems. Therefore, the objective of this study was to evaluate the steady-state hydraulic behavior of gate, ball, and pressure valves by analyzing ten different valves when open 25, 50, 75, and 100%, defined by total or partial handwheel or lever movement, using box plots, correlations, and principal components analysis, and grouping them using a dendrogram to determine similarities in hydraulic behavior.

METHODOLOGY

This study was conducted at the Hydraulics Laboratory of the Department of Water Resources of Universidade Federal de Lavras (UFLA), Lavras, Minas Gerais. A head loss test apparatus was set up in a pipeline network to enable control, monitoring, and data acquisition. The experimental module consisted of a constant head reservoir, pipes, valves, and pressure tapping collars. To measure the difference in head loss between two pipeline sections, "U" tube differential manometers, with mercury (Hg) and compressed air, respectively, as manometric fluids, were used for greater and lesser pressure differences. Figure 1 is a schematic overview of the testing apparatus setup.

The constant head reservoir's capacity was 1,000 liters, and its water level was controlled with a float value and a tank overflow device. The pipeline was made of rigid PVC, with 25- and 50-mm nominal diameters, and had two valves — a monobloc ball valve and a gate valve with 0.5- and 0.75-inch nominal diameters — for controlling and blocking flow.

The gate valve at the end of the apparatus (Figure 1, item 8) was used to adjust 15 test flowrates for each valve and openings, with 5 repetitions. The valves tested and their characteristics are shown in Table 1. Similar models of different types with 0.5- and 0.75-inch diameters were tested, as these sizes are most used in small building water networks.

Four different openings (25, 50, 75, and 100%) were evaluated, which were measured in relation to the total maneuver angles of the valves' levers or handwheel, depending on their type (Equation 1). This experimental decision was taken because, in this way, the results obtained could be more easily applied in the practice of Hydraulic Engineering, in addition to providing standardization regarding the comparison of results between the evaluated valves, due to their different construction and operation.

To ensure the definition of tested angles accuracy, a template with 360° indications, with a precision of 1° was fixed at the center of the valves' lever or handwheel before each test. After adjusting the openings of each valve, their levers or handwheels were externally locked, to prevent their movement during the essays.

$$\mathrm{Ro} = \frac{\mathrm{Ma}}{\mathrm{Ta}} \times 100 \tag{1}$$

Where:

Ro: relative valve opening (%);

Ma: valve maneuver angle tested position (degrees);

Ta: valve total maneuver angle (degrees).

Pipeline testing sections were designed using ten valve types with different diameters and manufacturing materials (Table 1).

To assist the perception regarding all types of evaluated valves' constructive and geometric specificities, of the mechanism for flow blocking and controlling, in addition to the flow section for 100 and 25% openings; and for the pressure valve, its specific inlet condition, Figure 2 is presented.

After establishing a steady-state flow regime, flowrates were estimated from the water mass collected in each test in a 20-litre container, using scales accurate to 0.01 kg. Collection interval was 30 seconds. Water density and kinematic viscosity were determined from the water's temperature (AZEVEDO NETTO; FERNÁNDEZ, 2015), using a mercury thermometer with a 0.2°C resolution.

Flow velocities were then calculated for the cross-section including a test valve. The resulting mean flow velocity (Figure 3A) and kinematic viscosity values were used to determine the Reynolds number (Figure 3B).

The tubing's absolute roughness (when a transient or fully turbulent regime was developed) and the minor head loss coefficient, K, associated with the linear section were recorded for each test (Equation 2), with different types of connection. This calibration was performed by minimizing the squared errors using the Solver packet from Excel® and the linear generalized reduced gradient (GRG) method, so that a residual minor head loss was determined for each test not associated with a tested valve.

$$\Delta H_{residual} = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} + \left(K \cdot \frac{v^2}{2g}\right) \quad (2)$$

Where:
f: friction factor, dependent on the Reynolds number (Re) and absolute pipe roughness (ε [m]) of the pipe's inner wall;
L: tube length (m);
D: pipe's internal diameter (m);

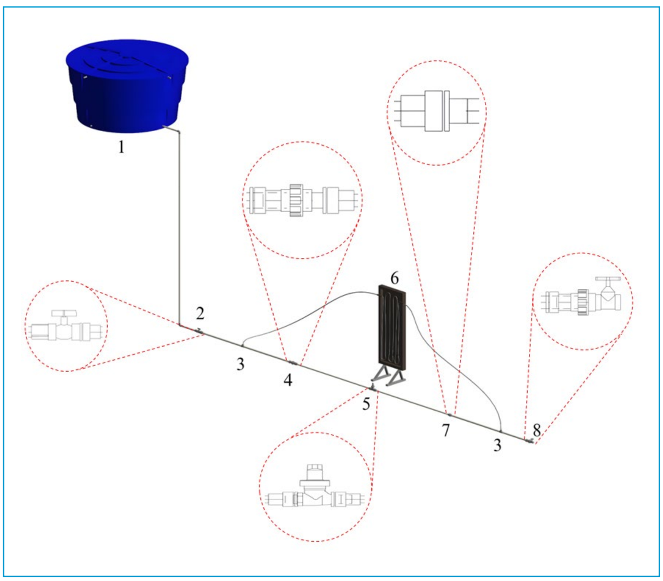


Figure 1 – Schematic of the experimental valve head loss testing apparatus setup. Caption: 1 - constant head reservoir; 2 - threaded sleeve - ball valve - weldable short adapter with slip and threaded fittings for valves; 3 - pressure tap collar; 4 - weldable adapter - threaded union - threaded reduction bushing - short weldable adapter; 5- short weldable adapter - valve to be tested - short weldable adapter; 6 - mercury manometer; 7 - threaded connection - short weldable adapter; 8 - short weldable adapter - gate valve.

v: mean flow velocity ($m \cdot s^{-1}$);
g: gravity acceleration ($m \cdot s^{-2}$);
K: the coefficient that depends on the singularity's geometry and the Reynolds number (dimensionless).

In Equation 1, f was calculated using the Hagen-Poiseuille equation for laminar flow regimes (Equation 3), the Blasius formula for hydraulically smooth turbulent regimes (Equation 4), and the Colebrook-White formula (Equation 5) for the other flow regimes.

$$f = \frac{64}{Re} \quad (3)$$

$$f = \frac{0.3164}{Re^{0,25}} \quad (4)$$

$$\frac{1}{\sqrt{f}} = -2 \log\left(\frac{\varepsilon/D}{3,71} + \frac{2,52}{Re\sqrt{f}}\right) \quad (5)$$

Where:
Re: Reynolds number (dimensionless);
ε: absolute pipe roughness (m).

The calibrated values of ε and K were then used to estimate the major head loss and that associated with the other test fittings. Thus, the head loss associated with the test valves could be isolated for each proportional opening and evaluated using Equation 6.

$$\Delta H_{valve} = \Delta H_{total} - \Delta H_{residual} \quad (6)$$

Where:
ΔH_{valve}: minor head loss estimated for the test valves at each proportional opening value (m);
ΔH_{total}: total head loss observed in the pipe system (m);
$\Delta H_{residual}$: estimated sum of the major and minor head losses in other fittings (m).

K was obtained using Equation 7, with the estimated minor head loss and the maximum velocity in the section.

$$K = \frac{hfl.\,2g}{v^2} \quad (7)$$

Table 1 – Characteristics of the evaluated valves.

Valve type	Acronym	ND (in)	Di (mm)	Do (mm)	C (mm)	Material
Gate	Ga1	½	20.14	20.14	26.45	Brass
	Ga2	¾	26.10	26.10	43.15	Brass
Ball - metallic	Bm1	½	21.90	21.90	47.26	Brass
	Bm2	¾	27.30	26.69	54.40	Brass
Ball - threaded monobloc	Bt1	½	22.00	20.45	73.34	PVC
	Bt2	¾	27.46	27.00	86.18	PVC
Ball – weldable monobloc	Bw1	½	21.45	21.55	62.80	PVC
	Bw2	¾	27.50	27.00	71.80	PVC
Pressure	Pr1	½	16.40	21.60	51.40	Copper, bronze, and brass alloy
	Pr2	¾	20.90	26.28	60.30	Copper, bronze, and brass alloy

ND: nominal diameter; Di: inlet diameter; Do: outlet diameter; C: valve length.

Where:

Hfl: minor head loss (m).

The equivalent length of the valves was calculated using Equation 8.

$$Leq = \frac{hfl.\,2g.\,D}{v^2.\,f} \quad (8)$$

Where:

Leq: the equivalent pipeline length for the fitting (m).

For the initial analysis, box plots of the minor head loss, the direct method K, and equivalent length were plotted as a function of the valve type and tested openings.

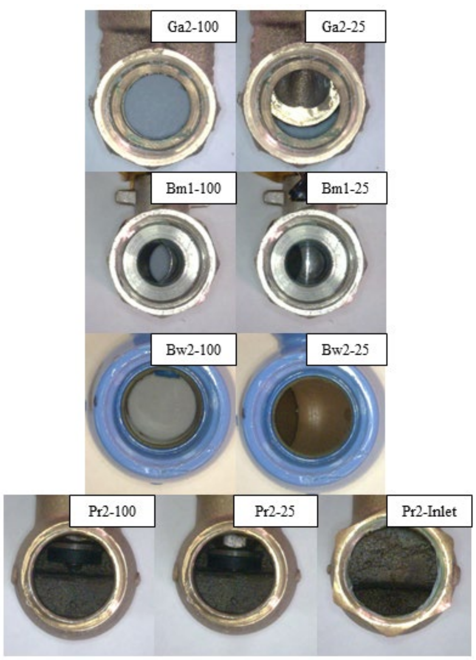


Figure 2 – Constructive and flow section specificities for some of the evaluated valves with 100 and 25% openings, and inlet detail of pressure valves.

Dependence between the independent variables were analyzed according to: maximum, minimum, and average flowrate; maximum, minimum, and average velocity; maximum, minimum, and average Reynolds number with the dependent variables, *i.e.*, maximum, minimum, and average head loss; maximum, minimum, and average K; and maximum, minimum, and mean Leq; a Pearson linear correlation matrix was determined, in which the Pearson correlation coefficient ($r_{x,y}$) between the variables X and Y is calculated using Equation 9 and results are a value between -1 and 1 (LOESCH; HIELTGEBAUM, 2012), considering a significance of α = 5%.

$$r_{x,y} = \frac{\sum_j x_j y_j}{\sqrt{\sum_j x_j^2}\sqrt{\sum_j y_j^2}} \quad \text{where} \quad \begin{cases} x_j = X_j - \bar{X} \\ y_j = Y_j - \bar{Y} \end{cases} \quad (9)$$

Where:

$\bar{X}$ and $\bar{Y}$: sample arithmetic means of variables X and $\bar{Y}$.

According to Vieira (2018), the correlation coefficient ($r_{x,y}$) can be classified according to its absolute value, as: "small or null" ($0 > r_{x,y} \geq 0.25$); "weak" ($0.25 > r_{x,y} \geq 0.50$); "moderate" ($0.50 > r_{x,y} \geq 0.75$); "strong" ($0.75 > r_{x,y} > 1.00$); and "perfect" ($r_{x,y} = 1.00$), where values below 0 represent a negative correlation.

Along with the correlation analysis, through principal component analysis (PCA), the more relevant variables in the dataset were determined, in addition to verifying how the valves at the various opening levels were related to the hydraulic variables associated with flow velocity and head loss, to aid in the interpretation of hydraulic behavior. The values of each valve's principal components were obtained through linear combination between the eigenvectors and the standardized original variables.

The variables were standardized into Z scores using Equation 10, to minimize interference that could be caused by the variables' magnitudes.

$$Z_{ij} = \frac{X_{ij} - \bar{X}_j}{S_j} \quad (10)$$

Where:

Z_{ij}: standardized variable of Xij;

X_{ij}: variable with attribute j and object i;

$\bar{X}_j$: arithmetic mean of variable j;

S_j: sample standard deviation of variable j.

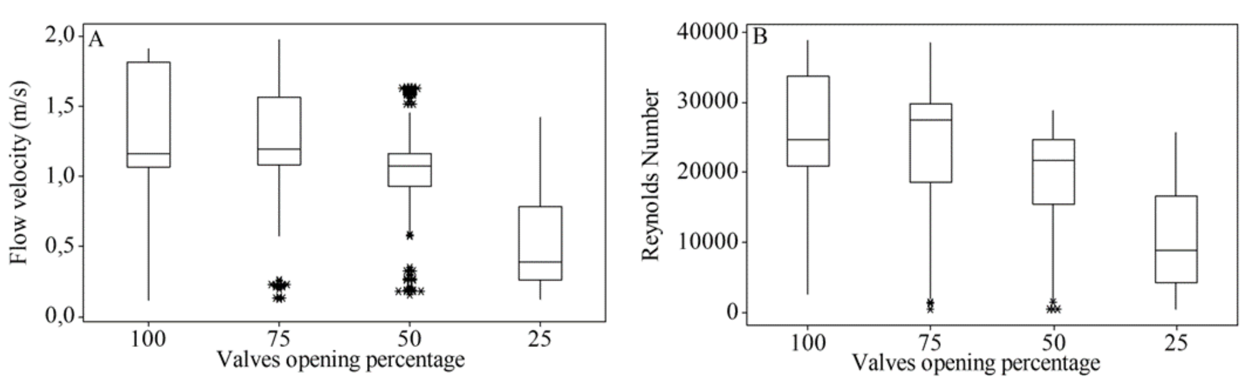


Figure 3 – (A) Flow velocity and (B) Reynolds number in the test valves.

An analysis of hierarchical clusters was also performed using the dependent and independent variables evaluated by the correlation matrix, in order to cluster the cases composed of the valve and relative opening combinations. The distance between the standardized variables was calculated using Equation 11, using Ward's method (WARD, 1963) to delineate the clusters.

$$d_{ii`} = \sqrt{\Sigma(Z_{ij} - Z_{i`j})^2} \quad (11)$$

Where:

$d_{ii`}$: Euclidean distance between standardized variables $Z_{ij}$ and $Z_{i`j}$.

RESULTS AND DISCUSSION

Figure 4 shows the box plots of hfl as a function of the proportional opening of the valves. In general, the detected outliers are related to the wide range of tested flowrates, controlled by the outlet valve (downstream the hydraulic setup), combined with the relative openings of the tested valves. So, the outliers were not disregarded from the analysis, since that was one of the actual purposes of this work.

Figure 4A shows that valves Pr1 and Pr2 had the highest hfl values, while the lowest hfl value was observed for valve Bt2. For valve Bw2, the variation in head loss was small, while in valves Pr1 and Pr2, a large head loss interval was obtained for the different flowrates (Figure 4A).

For valves Ga1 to Bw2, following the order presented in Table 1 and Figure 4, a larger cross-section available for flow was proportionally verified in relation to the outer diameter of the valve, unlike what was found for pressure valves, whose internal path available to the flow was restricted in relation to the body of the device as a whole. For valves Pr1 and Pr2 (pressure valves), the plug acted vertically, controlling the passage of water in a section of reduced dimensions, which implied in a generally high head loss for the opening of 100% in relation to that of the others evaluated (gate and ball); and a head loss that changed with the variation in the test flowrate for the aforementioned level of opening (Figure 4A).

For the 100% open valves (Figure 4A), in general, the lowest head loss values were observed for the ball valves. According to Menon (2015), this is due to the low resistance to flow offered by ball valves in the fully open position, a resistance considered small even when compared to that of the gate valve. Parisher and Rhea (2021) state that, due to the low resistance, associated to head loss occurrence, with the use of ball valves, higher regnant pressure values may be available in the system compared with other devices that produces higher minor head losses, however, in this study, this fact was more observed for gate valves, when evaluating the behavior for all openings.

Amaral and Amaral (2016) evaluated the factors that influence head losses in pipelines and fittings and noted that there are several ones related to the occurrence of hfl: nature of the flowing fluid, nature of the pipe walls, tube diameter and, consequently, the cross-section available to flow, material ageing, flow regime of the fluid, and flow velocity. Thus, it can be inferred that the geometry of the pressure valves leads to higher head losses depending on the flowrate, even when the valve is 100% open. Gate, ball, and pressure valves, even when completely open and having the same nominal diameter, do not have the same internal area, that is permissible for water flow, mainly the pressure valve. For gate and ball, water passes through the valve in the same direction acquired by the flow, that is, directly through the valve. In the case of the pressure valve, considering that it is installed horizontally, the water flow collides with a vertical face inside the valve body, changing its direction from horizontal to vertical downward and then vertical upward, it is discharged through an orifice, collides with the valve obturator and then returns to the horizontal direction (Figure 2). In this way, one can note the reason why the minor head loss in the pressure valves is higher compared to ball and gate valves when they are 100% open.

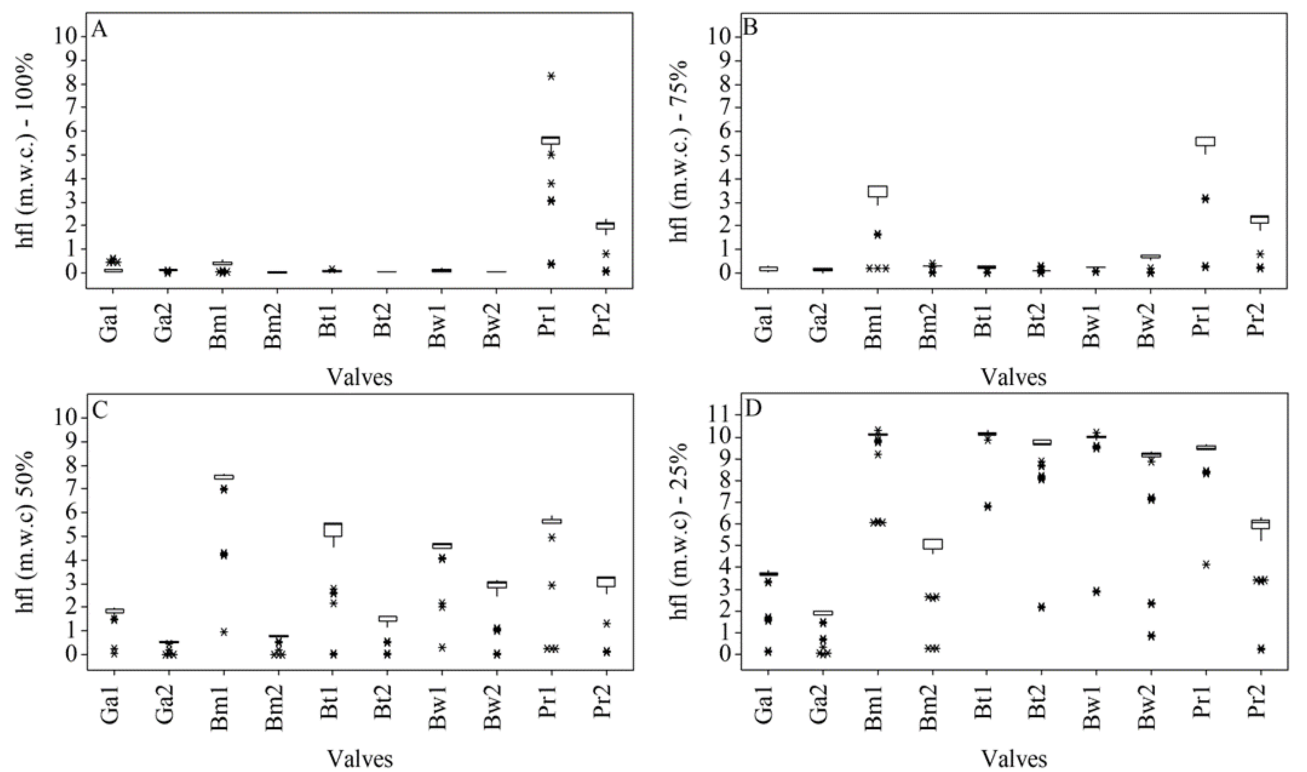
Figure 4B shows that valves Ga1, Ga2, Bm2, Bt1, Bt2, Bw1, and Bw2 led to minimal changes in hfl for the different flows, while the behavior of valves Pr1 and Pr2 was similar to that observed for the 100% open valve (Figure 4A). When valve Bm1 was 75% open, regarding the valve lever step, the mean hfl was higher than that obtained for the 100% open valve (Figure 4A), which did not occur for the other ball (Bm2, Bt1, Bt2, Bw1, Bw2) and gate (Ga1 and Ga2) valves.

Thus, the hydraulic behavior of valve Bm1 (metallic ball ½") was the most sensitive to the opening degree in terms of the occurrence of minor head loss. In the evaluated model, there was an inner ring near the walls of the valve (Figure 2 – Bm1), which reduced the cross-sectional area available to flow in this device, in addition to causing additional head loss. Comparatively, a valve similar to this one (Bm2- metallic ball ¾"), with decreasing opening level, did not exhibit similar behavior because it had a larger internal diameter and did not have an inner ring of relevant proportions.

More evident differences between the internal permissible flow area of the ball valve, compared to the gate valve, are highlighted when they are progressively closed. For the ball valve, when 50% of its lever is closed (*i.e.*, for the possible 90° of closure there is a position of 45° on the lever), the internal area permissible for water flow is less than 50%, due to the construction and operation form of the ball valve flow blocking mechanism. Silva *et al.* (2008) obtained a higher hfl when they reduced the tested valves flow cross-section, which was practically negligible when it was open. Although most ball valves did not show significant changes in hfl when they were 75% open (Figure 4B), according to Stewart (2016), when some types of ball valves are subjected to partial opening under certain pressure conditions, they may present a locking of the ball. Thus, despite the possibility of its use for moderate control (with the evaluation of Figure 4C, some flow control can be achieved with the ball valve at relative opening around to 50%), usage recommendation is to start and stop the flow, *i.e.*, to block it (STEWART, 2016).

For valves Pr1 and Pr2, the behavior was similar to that obtained at 75% open due to the variation in flow velocity and flowrate. Haque *et al.* (2010), for a 40% open valve, obtained a greater head loss with increasing flow velocity. Figure 4D also shows that the ball valves (Bm1, Bt1, and bw1) obtained higher hfl, which led to low flowrates and flow velocities when dynamic equilibrium conditions were reached.

Interestingly, for valves Ga1 and Ga2 (gate) and Bm2 (metallic ball of ND ¾"), there were no greater variations in head loss occurred between the treatments at 50% and 25% open. This occurred due to a variation in the flow velocity in the gate valves resulted from small circulation of the fluid in the cross-sectional area, which was expected, as the head loss was partly due to the fluid passage area, which decreased as the valve was closed. For valve Bm2 (metallic ball of ND ¾"), the flow velocity variation occurred due to fluid circulation in the internal part of the ball, as the diameter of the inner part of the valve has a small-scale inner ring, compared to its whole inner diameter. Costa (2015)



*Outliers.

Figure 4 – Minor head losses for proportional opening values: (A) 100%, (B) 75%, (C) 50%, (D) 25%.

obtained a lower hfl when the valve was completely open, with no significant flow disturbances.

For most ball valves (Bm1, Bt1, Bt2, Bw1, and Bw2), there was an excessive increase in hfl values from 100 to 50% opening, which led to lower flow velocities and flowrates under steady-state conditions, while this fact was observed for Bm2 only for the 25% opening. In the threaded ball and PVC (Bt1, Bt2, Bw1, and Bw2), there was a low relative roughness that provided high Re values, which characterized a more relevant turbulence during the flow. Porto (2006) explains that with the presence of accessories or connections in water supply systems, there is a change in the modulus or direction of flow lines at average velocity and, consequently, in pressure, which is reflected in an increase in turbulence that produces water head losses.

For pressure valves, at 25% open, the mean hfl increased compared to that of previous conditions. In a direct way, the more a valve is opened, under dynamic equilibrium conditions, the greater the flow capacity through the network, *i.e.*, a higher flowrate than that of when the opening of the cross-section was reduced, with a higher hfl and a lower flowrate, but it is important to assess the impedance of the water network to its change of flow state. Building water networks have low impedance because they are short, which makes valve maneuvers lead to proportionally easier flow control, compared to large distribution networks.

Figure 5 shows that the values of the head loss coefficient (K) vary greatly, both with the percentage opening and the particular characteristics of each evaluated valve.

Figure 6 shows box plots of equivalent lengths (Leq) due to the proportional valves opening, and valve type and/or model.

Figures 5A and 6A show that valves Pr1 and Pr2 had the highest observed K and Leq values. Conversely, the lowest values were found for valve Ga1. This is consistent with the results obtained in the study conducted by Wu, Li and Gao (2019), where even for a diameter different from those studied for this paper, the K for a fully open gate valve exhibited values close to 0. For valves Pr1 and Pr2, the values of K and Leq were higher due to their higher hfl values even at lower steady-state flowrates. For valves Bm1 and Bm2, it was found that the values of K and Leq were lower, once that in the steady state, higher flowrates and, consequently, higher mean flow velocities were obtained when the downstream flow controller valve was opened. Consequently, there was an increase in Re and a decrease in hfl. Haque *et al.* (2010) obtained lower K values with increasing opening percentage. Additionally, according to the authors, as the cross-sectional area increased, the flow became uniform and less turbulent.

Figures 5B and 6B show that valves Bm1, Pr1, and Pr2 had the highest values of K and Leq and that the lowest values occurred in valve Ga1. It was also found that for valves Bm2, Bt1, Bt2, Bw1, and Bw2, the variation in K and Leq was lower, while valves Ga1, Ga2, Pr1, and Pr2 exhibited a behavior similar to that observed for a 100% open valve. Conversely, valve Bm1 exhibited a slight increase in K and Leq values because, with high hfl values (Figure 4B), there was a lower flowrate and velocity once the flow was stabilized.

In contrast, according to Figures 5C and 6C, for ball valves (Bm1, Bt1, Bt2, Bw1, and Bw2), greater variation in the flow velocity, and consequently Re, was obtained with the movement of the downstream flow controller valve (Figure 1 – item 8), which provided high hfl values. For a relative opening of 50%, there was greater variation in the values of K and Leq in the ball valves due to the variation in flowrate and, consequently, flow velocity and hfl obtained in the downstream valve; however, in valves Ga1, Ga2, Pr1, and Pr2, the variation was lower.

Valves Bm1, Bt1, Bt2, and Bw1 led to the highest values of K and Leq, and the lowest value was found in valve Ga2 (Figures 5D and 6D). For the smallest opening, the lowest flowrates were measured under stable flow conditions and, therefore, the lowest velocity. With this and with greater head loss, higher K values were obtained. There was also a large variation in the values of K and Leq (Bm1, Bt1, Bt2, Bw1 and Bw2). In contrast, the variation associated with valve Bm2 was small due to the small variation in the flow velocity during the tests. In valves Bt1, Bt2, Bw1 and Bw2, higher magnitudes of K and Leq were observed due to the lower flow velocity and the high hfl values obtained. The observation of the vertical axis of Figure 5D shows that the scale of the K value was much larger than those obtained for the other openings. According to Razaey (2020), in the initial stages of valve opening, the rate of change in the head loss coefficient is very pronounced, thus explaining this discrepancy.

With their work, Poręba *et al.* (2018) evaluated minor head losses coefficients for DN 15 angle and globe valves, for variable degrees of closure and different values of flowrate, as was done in this research. Their results showed a dependence between the head loss and coefficients with the degree of valve closure, in the same way as detected in this study, and as the tested valves had different construction, the authors also found significant differences between the head loss for angle and globe valves for the same opening/closure degree.

Based on the results obtained, ball valves are more efficient for blocking flow compared to gate valves, in which there is a relevant increase in head loss only from a relative opening of 25%. This fact also implies that, between this percentage of opening and total closing, they can exert some control, which, depending on the angular distance covered, may represent interesting precision in maneuvering its handwheel. For the ball valve, even with this possibility of controlling the flow from 50% of relative opening until total closing, as they have a ¼ turn lever, the precision of the maneuver would be low. As for the use of gate and ball valves for energy dissipation, in cases that there is need to reduce the pressure downstream of these devices, the latter proved to be more efficient.

Table 2 shows the correlation matrix between the independent (Q, V, and Re) and dependent variables (hfl, K, and Leq) for the tests performed.

In gravity flow water distribution, the physical constitution of the pipeline plays a fundamental role in the maximum flowrate when considering a steady-state regime. Changing the valve type present in the network or even closing an accessory leads to a new equilibrium situation, which implies a new water flow capacity. In this study, a holistic analysis of Figures 4, 5, and 6, in addition to Table 2, shows that closing the test valves reduced the maximum flowrate and, consequently, the mean velocity in the flow section and Re (Figure 3) due to a greater head loss in the fittings studied, since the energy available to the flow was always the same.

According to Wu, Li and Gao (2019), who investigated the hydraulics of a gate valve, the opening degree of the valve has a great influence on Q and K, *i.e.*, as the valve closes, K increases rapidly and Q decreases, a fact also proven in this study. Similar behavior was also reported by Ozdamar *et al.* (2007), who described the relationships between the ball valve opening degree and K.

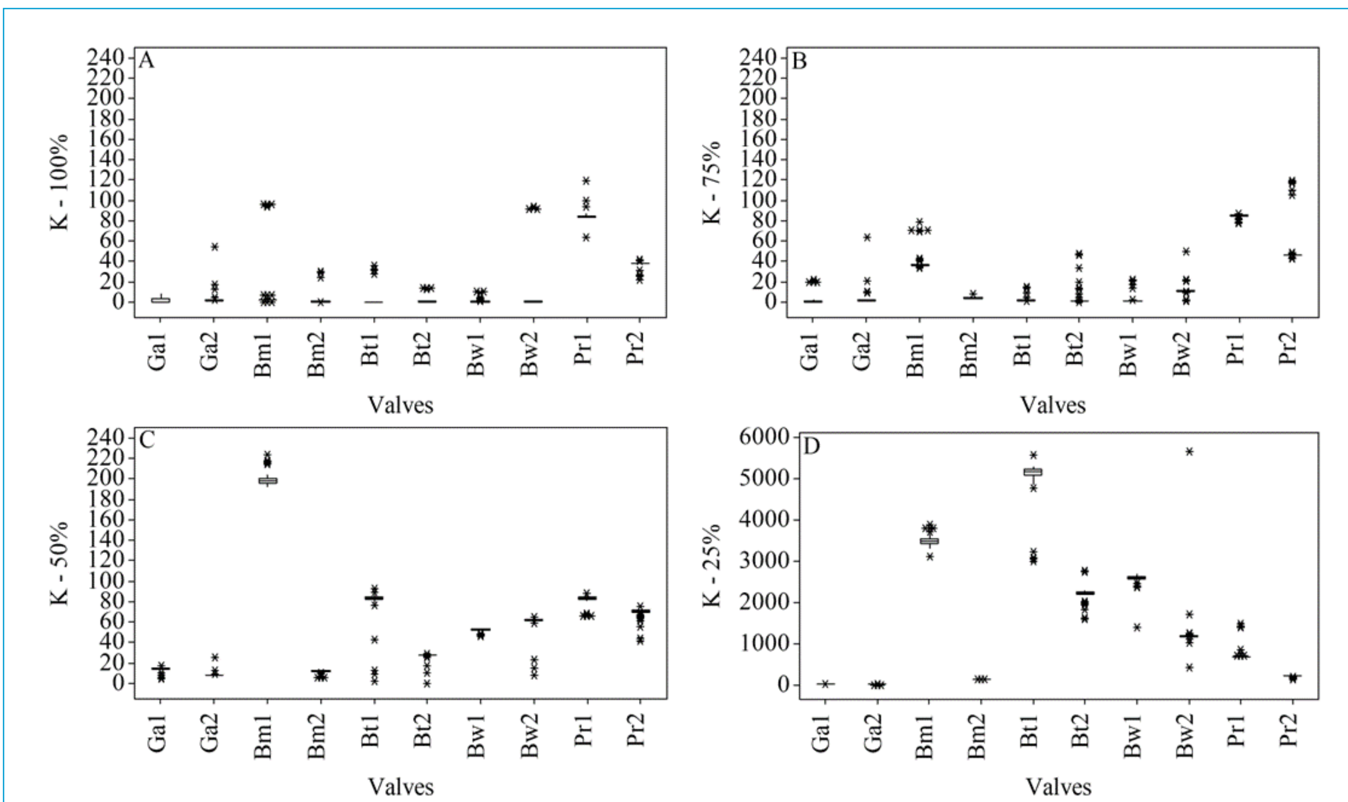


Figure 5 – Coefficient of the head loss at different proportional openings, (A) 100%; (B) 75%; (C) 50%; and (D) 25%.

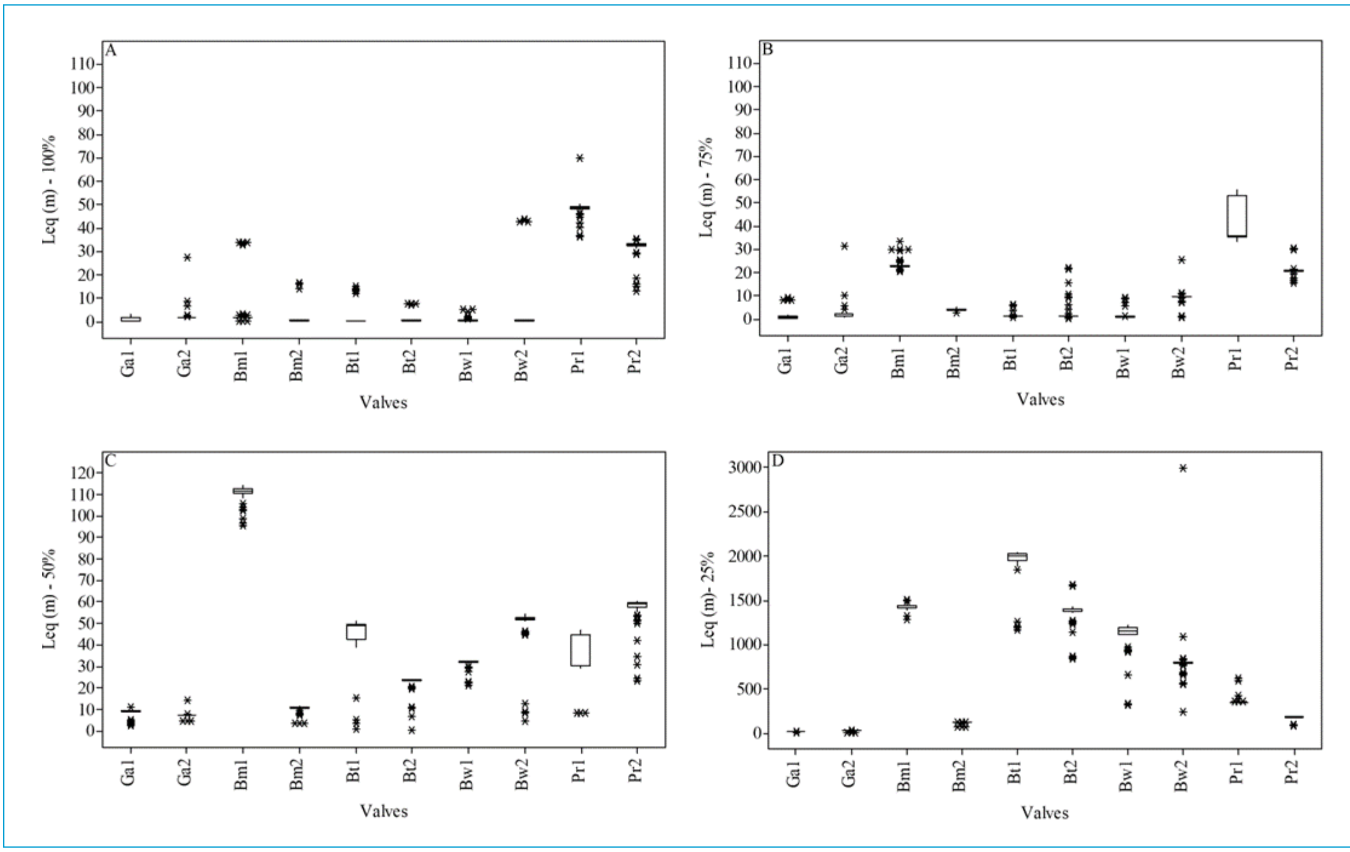


Figure 6 – Equivalent length for different proportional openings, (A) 100%; (B) 75%; (C) 50%; (D) 25%.

Therefore, negative correlations were obtained between the hydraulic variables related to flow and the hydraulic variables related to head loss (Table 2). Obviously, in a quick calculation of head loss, with increasing flowrate or velocity, the estimated head loss increased as a physical phenomenon; however, there were multiple distinct processes in the present study. Closing the valves not only influenced the increases in hfl, K, and Leq but also reduced flow velocity and Re (Figure 3), providing a negative correlation.

In general, the maximum and minimum velocities of the tests were not correlated with hfl, K, or Leq, except for the maximum Leq and average Leq, which exhibited weak negative correlations, according to Vieira (2018), with the minimum and average velocities. Additionally, the minimum Re was only correlated with maximum K, mean K, and mean Leq, but all these correlations were negative and weak (VIEIRA, 2018). According to Porto (2006) and Chern, Wang and Ma (2007), K does not vary with the Reynolds number or even has a small variation with Re, with these values being generally constant for Re greater than 10^5, reinforcing the results obtained in this study. Not only the abovementioned authors but also several studies published in the literature conclude that K is independent of Re (MOUJAES; JAGAN, 2008) for the values normally obtained for Re in water flow in engineering applications.

The maximum and mean flowrates showed almost perfect strong negative correlations (-0.990) with the maximum and mean hfl (VIEIRA, 2018), which proved that the lowest hfl was obtained for the highest flowrates (gate valves and 100% openings, in general) because the lowest flowrates were the result of the highest hfl in the valves, as tested (pressure valves and smallest openings).

In general, the maximum and average flowrates of the tests were more correlated with the hydraulic variables relative to hfl than the minimum flowrates, and only the mean velocity of the tests correlated with the hydraulic variables relative to hfl. The mean Re of the assays was better correlated with hfl, K, and Leq.

The correlation analysis of this study showed results similar to those observed by Haque *et al.* (2010). These authors also observed that as the flowrate increased, there was a decrease in minor head loss and the K coefficient, which led to a decrease in the equivalent length, since the limiting element of the flowrate was the closing of the test valve, which dissipated the energy available to the flow rather than the flow.

PCA showed that only the variable v_{max} did not show significant discriminatory power in Principal Component 1 (PC1) and that the hydraulic variables related to the minimum velocities (v_{min}, Q_{min}, and Re_{min}) were well represented by Principal Component 2 (PC2). The other variables had important discriminatory power in PC1, with the variables represented by or relating to velocity positively correlated with PC1 and the variables related to head loss negatively correlated.

Then, the principal components biplot analysis (Figure 7) allows to observe that several valves with a relative opening of 25% had hydraulic behavior characterized by a significant head loss, namely, Bt1-25, Bm1-25, Bt2-25, Bw1-25, Bw2-25, and Pr1-25, in decreasing order, *i.e.*, most ball valves. These valves have the main objective of blocking flow, and according to these results, they are more efficient for this purpose than gate valves.

Table 2 – Correlation matrix between the independent variables (Q, V, and Re) and dependent variables (hfl, K, and Leq).

Independent variables	Dependent variables								
	hfl_{max}	hfl_{min}	Hfl_{av}	K_{max}	K_{min}	K_{av}	Leq_{max}	Leq_{min}	Leq_{av}
Q_{max}	-0.990	-0.743	-0.991	-0.763	-0.761	-0.768	-0.666	-0.756	-0.803
Q_{min}	-0.340	-0.334	-0.367	-0.476	-0.442	-0.472	-0.363	-0.402	-0.456
Q_{av}	-0.977	-0.763	-0.991	-0.791	-0.789	-0.799	-0.681	-0.779	-0.832
V_{max}	-0.161^{NS}	-0.146^{NS}	-0.168^{NS}	-0.158^{NS}	-0.147^{NS}	-0.150^{NS}	-0.140^{NS}	-0.147^{NS}	-0.157^{NS}
V_{min}	-0.085^{NS}	-0.056^{NS}	-0.122^{NS}	-0.359	-0.262^{NS}	-0.299^{NS}	-0.331	-0.254^{NS}	-0.328
V_{av}	-0.784	-0.580	-0.807	-0.659	-0.637	-0.645	-0.592	-0.641	-0.692
Re_{max}	-0.762	-0.540	-0.774	-0.593	-0.586	-0.592	-0.527	-0.583	-0.623
Re_{min}	-0.241^{NS}	-0.113^{NS}	-0.259^{NS}	-0.312	-0.286^{NS}	-0.328	-0.191^{NS}	-0.226^{NS}	-0.313
Re_{av}	-0.823	-0.563	-0.834	-0.625	-0.618	-0.628	-0.545	-0.609	-0.659

^{NS}Not significant; max: maximum, min: minimum; av: average.

With the analysis of Figures 4D, 5D, and 6D, clearly, in general, there were greater minor head losses accompanied by higher K and Leq coefficients for ball valves in comparison to the others evaluated. Additionally, according to the position of these valves with 25% openings in the biplot (Figure 7), they were the ones least related to the hydraulic variables associated or obtained with flow velocity, that is, for these valves, the lowest velocities, flows, and mean Re were obtained in this relative opening condition.

Figure 8 shows the analysis of hierarchical clustering using a dendrogram, considering the combinations of valves and the evaluated openings as dependent variables.

To form the clusters, cuts in the dendrogram were applied as a function of the variance between combinations of the studied valves and their different openings. These cuts were made so that the groups formed had the greatest internal similarity, *i.e.*, with increasing connection distance, similarity decreases, and the distance for the formation of new groups increases. This was performed with the analysis of the connection distances in each step of the amalgamation process and, as a result, three groups were formed.

The first group is formed by cases Bm1-25, Bt1-25, Bt2-25, Bw1-25, and Bw2-25, *i.e.*, all with 25% openings. This group has particularly high values of minor head loss (hfl), K coefficient, and equivalent length (Leq), which can be attributed, notably, to the small openings of the valves and, consequently, a small permissible area for water flow, which leads to significant energy dissipation (Figure 2); these are, then, the most prominent conditions for blocking the water flow, as already verified by PCA.

The second group is formed by cases Bm1-50, Bm2-25, Bt1-50, Pr1-25, Pr1-50, Pr1-75, Pr1-100, Pr2-25, and Pr2-75, treatments with different diameters and openings, but with a predominance of pressure valves, even with an opening of 100%, which indicates a similarity of the hydraulic variables behavior due to the geometry, form of construction, and inlet condition of these valves (Figure 2) and their consequence on the variables associated to minor head loss. Pressure valves are mainly applied in engineering flow control, especially in residential showers. In this grouping, valves Pr1-25, Bm1-50, Bt1-50, Pr1-50, and Pr1-75 have the highest hfl, K, and Leq values, and there is similarity in the values of these variables at these openings. As already discussed for Figure 4C, ball valves under these conditions would be used for flow control, even without good precision.

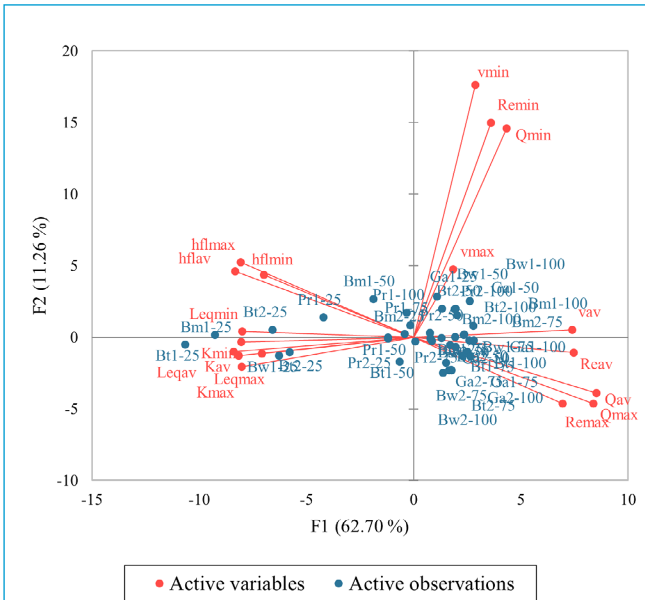


Figure 7 – Biplot of the valve PCAs for the openings and hydraulic variables. Note: max: maximum, min: minimum; av: average; 100: 100% opened; 75: 75% opened; 50: 50% opened; 25: 25% opened.

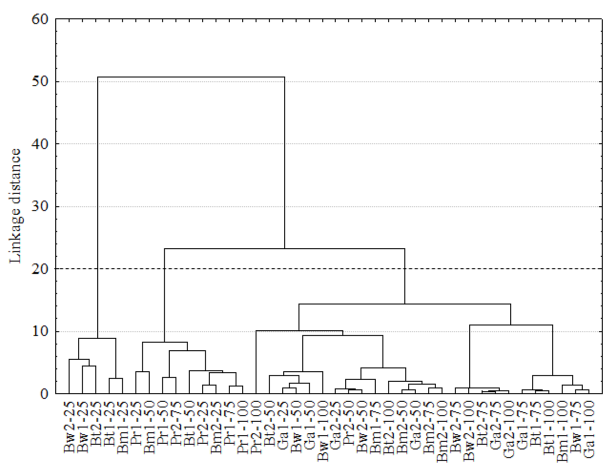
The third group, which is larger, has a predominance of cases with the largest openings or even treatments without noteworthy head losses, coefficients K, and Leq, even with smaller percentages of openings; thus, the valves in these situations may exert some, but practically irrelevant, flow control. It is important to note that the gate valves in all situations of relative opening are allocated to this third group; thus, it is seen that they are efficient for flow blocking only when practically closed, at relative openings below 25%, which are not evaluated in this study, unlike ball valves, which have a large capacity to reduce the flow through the pipeline and dissipate energy at 50% relative openings and reduce the flow to almost nothing, *i.e.*, blocking it, with a 25% relative opening.

The presence of Pr2-100 in group 3 is worth highlighting, since pressure valves are used for flow control; though for this experimental treatment, it was in a condition that exerts the least energy dissipation (Figure 2), *i.e.*, 100% open.

However, Pr2 with 100% opening was classified at one end of the group, next to group 2, which denotes similarities with this one, and without forming a subgroup with any other valve (Figure 8) from its group. This result, different from that observed for Pr1 for the same opening, is due to their different nominal diameters and, as expected, there was a lower minor head loss associated with Pr2, which has a nominal diameter of ¾” (Figure 4A).

Finally, a summary of the average obtained K and Leq values, for the highest tested flowrate at each treatment, and their standard deviation, is presented in Table 3.

It was possible to observe in Table 3 that there was a major increase when comparing the K values of the fully open valves (100%) to those with 25% opening. These values were lower for some valves, such as 506, 697, and 1,949%, for Pr2, Pr1 and Ga2, respectively; and higher for others, such as 122,084, 288,527 and 1,090,111%, for Bm1, Bw1 and Bt1, respectively. When studying DN 15 angle valves, Poręba *et al.* (2018) found that an increase of minor loss coefficient was greater than 1,600% when changing valve opening from fully open to 25%, a similar value to those found for Pr2, Pr1, and Ga2 in this study. The physical conditions that lead to this can be seen in Figure 2.



100: 100% opened; 75: 75% opened; 50: 50% opened; 25: 25% opened.

Figure 8 – Hierarchical cluster analysis dendrogram for valves and the proportional opening.

Veról, Vazquez and Miguez (2021) suggest the use of K values for pressure valves as recommended by the NBR 15704-1 Standard (ABNT, 2011), of 40 and 32, for 1/2” and 3/4” valves, respectively. Despite the flow ranges for determining the suggested K values being higher than those used in this work, comparing the K values presented in Table 3, it is noticed that these are not compatible, even for the valves with full opening (100%). Thus, the suggested values should be carefully used since they may lead to an undersizing of the water supply building system.

Still as an example of a minor head loss coefficient value suggested in the Brazilian literature, Baptista and Coelho (2016) adopt as Leq of pressure valves, for a water supply building system, in a shower branch, the value of 11.1 m for ½” nominal diameter, probably due to the lack of availability of specific data for this valve type. This value is small, even when compared to that obtained in this study, for the same type of device, considering the 100% opening, thus, its use would lead to an underestimation of the head loss in the considered pipeline section and, as a consequence, this could be undersized.

CONCLUSIONS

In estimating hfl, K, and Leq for the valves, higher values were obtained for proportional openings of 25% due to the smaller cross-sectional area available for flow and lower flow velocity. The lowest values of these variables were determined for the 100 and 75% openings, and the pressure valves showed high values even for these.

In the correlation analysis, the maximum and mean flow of the tests were most correlated with the hydraulic variables related to hfl, and only the average velocity of the tests, in general, correlated with the hydraulic variables related to hfl. Thus, it was also concluded that the maximum and minimum velocities were not correlated with hfl, K, or Leq. On the other hand, the

Table 3 – Average and standard deviation of K and Leq values for the different evaluated valve types and openings, for the highest tested flowrate in each treatment.

Valve	Opening							
	100%		75%		50%		25%	
	K	Leq	K	Leq	K	Leq	K	Leq
Ga1	0.57 ± 0.15	0.37 ± 0.10	1.48 ± 0.09	0.95 ± 0.06	14.23 ± 0.22	8.85 ± 0.13	37.20 ± 0.24	22.68 ± 0.14
Ga2	1.76 ± 0.02	1.58 ± 0.02	2.51 ± 0.11	2.22 ± 0.10	8.20 ± 0.04	7.26 ± 0.04	36.06 ± 0.14	30.67 ± 0.12
Bm1	2.82 ± 0.06	1.81 ± 0.04	37.16 ± 0.27	22.65 ± 0.15	196.41 ± 1.18	110.66 ± 0.63	3445.59 ± 24.69	1431.66 ± 9.01
Bm2	0.56 ± 0.07	0.45 ± 0.05	4.40 ± 0.39	3.93 ± 0.35	12.14 ± 0.22	10.44 ± 0.18	163.37 ± 2.02	123.63 ± 1.37
Bt1	0.47 ± 0.04	0.30 ± 0.03	1.92 ± 0.04	1.22 ± 0.03	84.22 ± 0.81	49.60 ± 0.45	5123.99 ± 104.49	1988.05 ± 35.07
Bt2	1.07 ± 0.05	0.87 ± 0.04	1.34 ± 0.12	1.19 ± 0.10	28.31 ± 0.21	24.20 ± 0.17	2262.31 ± 11.70	1405.56 ± 6.85
Bw1	0.89 ± 0.11	0.57 ± 0.07	1.44 ± 0.03	0.92 ± 0.02	53.29 ± 0.46	32.19 ± 0.26	2568.78 ± 60.49	1162.39 ± 23.56
Bw2	1.14 ± 0.04	0.98 ± 0.03	11.06 ± 0.12	9.71 ± 0.10	62.26 ± 0.35	52.52 ± 0.27	1300.27 ± 237.72	857.31 ± 133.85
Pr1	85.24 ± 0.38	49.70 ± 0.21	85.09 ± 0.62	35.70 ± 0.25	82.96 ± 0.90	29.92 ± 0.28	679.43 ± 6.49	343.79 ± 2.95
Pr2	38.85 ± 1.59	33.36 ± 1.23	46.55 ± 0.32	20.97 ± 0.14	71.55 ± 0.32	59.97 ± 0.27	235.37 ± 1.05	183.73 ± 0.76

average Re correlated better with hfl, K, and Leq. By PCA, it could be possible to determine that ball valves have greater flow blocking capacity than gate valves, even though both are intended for this purpose, due to its high head loss already at 50% of relative opening, which implies that it can exert some control to the flow.

Three valve groups were verified among those studied, concluding that the first group had high values of hfl, K, and Leq due to smaller openings in the valves. However, the second group had a predominance of treatments with intermediate openings and even fully open pressure valves, there was a similarity of the hydraulic variables values due to the geometry and construction of the valves. For the third group, which in general showed the lowest values of hfl, K, and Leq, there was a predominance of cases in with the largest openings, except for gate valves.

AUTHORS' CONTRIBUTIONS

Nhamússua, S.M.S.: Data curation, Investigation, Formal Analysis, Writing – original draft. Thebaldi, M.S.: Conceptualization, Formal Analysis, Methodology, Project administration, Writing – review & editing. Lima, E.M.C.: Investigation, Methodology. Fiais, P.R.F.: Investigation, Formal Analysis. Silva, M.A.: Formal Analysis, Writing – review & editing. Deus, F.P.: Writing – review & editing.

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