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Effect of hydraulic and geometric factors upon leakage flow rate in pressurized pipes

Efeito de fatores hidráulicos e geométricos sobre a vazão através de vazamentos em condutos pressurizados

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ABSTRACT

Computational Fluid Dynamics (CFD) simulations of a leakage in a pressurized pipe were undertaken to determine the empirical effects of hydraulic and geometric factors on the leakage flow rate. The results showed that pressure, leakage area and leakage form, influenced the leakage flow rate significantly, while pipe thickness and mean velocity did not influence the leakage flow rate. With relation to the interactions, the effect of pressure upon leakage flow rate depends on leakage area, being stronger for great leakage areas; the effects of leakage area and pressure on leakage flow rate is more pronounced for longitudinal leakages than for circular leakages. Finally, our results suggest that the equations that predict leakage flow rate in pressurized pipes may need a revision.

Keywords: CFD; Factorial design; Leakage area; Leakage flow rate; Leakage form; Pressurized pipe.

RESUMO

Simulações com Fluidodinâmica Computacional (CFD) de um vazamento em um conduto pressurizado foram realizadas para determinar os efeitos empíricos de fatores hidráulicos e geométricos na vazão através do vazamento. Os resultados mostram que a pressão, área de vazamento e forma do vazamento, influenciaram a vazão significativamente, enquanto que a espessura do tubo e a velocidade média não influenciaram a vazão através do vazamento. Com relação às interações, o efeito da pressão sobre a vazão depende da área do vazamento, sendo maior para áreas de vazamento maiores; os efeitos da área de vazamento e pressão na vazão através do vazamento é mais pronunciada para vazamentos longitudinais em comparação a vazamentos circulares. Finalmente, nossos resultados sugerem que as equações que predizem vazão através de vazamentos em tubos pressurizados precisam passar por uma revisão.

Palavras-chave: CFD; Planejamento fatorial; Área de vazamento; Vazão através de vazamento; Forma do vazamento; Tubo pressurizado.

INTRODUCTION

Leakages in the pipes that transport fluids like oil, industrial gas, and water could cause serious environmental, social, economic, and health and safety issues (Razvarz et al., 2020). Bad pipe connections, defects in pipes (e.g., corrosion, pipe age), mechanical damage caused by excessive pipe load (e.g., traffic on the road above, damage due to excavation), and high system pressure can all lead to pipeline leakage (Puust et al., 2010). Visual line walking checking, direct mechanical excavation, and model-based procedures are all options for detecting and locating a leakage (Abdulshaheed et al., 2017). In the context of hydraulic model-based techniques, an understanding of the behavior of individual leaks is critical to modeling its behavior as accurately as possible, because system leakage is made up of a large number of individual leakages.

A leakage is generally compared to an orifice, for which the well-known Torricelli equation describes the relationship between flow rate q as a function on the leakage effective area $C_d A$ – defined as the product of the discharge coefficient C_d and of the leakage area A – and on the pressure head h by the orifice flow Equation 1

$$q = C_d A\left(2gh\right)^{0.5} \tag{1}$$

where g is the gravitational acceleration. Equation 1 predicts q through an interaction between C_d, A, g, and h. However, the variation of A and C_d with pressure has been widely discussed in recent years (Walski et al., 2006, Greyvenstein, 2007, Cassa et al., 2010, Cassa & van Zyl, 2014). To consider this effect, a power law Equation 2 was introduced:

$$q = ah^N \tag{2}$$

where a is the leakage coefficient, and N is the leakage exponent. A large range of leakage exponents have been reported in the literature, the vast majority are between 0.5 and 1.5 (Schwaller & van Zyl, 2015). Equation 2 predicts q through an interaction between a and h, and is coincident with Equation 1 when $a = AC_d(2g)^{0.5}$ and $b = 0.5$. The term $ah^{B-0.5}$, which expresses the differences between Equation 1 and 2, can be explained by the variation of AC_d, and hence of a, with h (Ferrante et al., 2014). Assuming that A varies linearly with h and that the pressure response of a leakage can be characterized by its initial area (under zero pressure conditions), A_0, the area of leakage openings as a function of pressure can be described with the Equation 3:

$$A = A_0 + mh \tag{3}$$

where m is the pressure head-area slope. Replacing Equation 3 into Equation 1 results in the FAVAD equation (4) (Greyvenstein, 2007, Cassa et al., 2010, Cassa & van Zyl, 2014)

$$q = C_d (2g)^{0.5}\left(A_0 h^{0.5} + mh^{1.5}\right) \tag{4}$$

The first term of Equation 4 describes leakage through the initial area of the leakage while the second part of Equation 4 describes the leakage through the expanding part of the leakage. Equation 4 coincides with Equation 1 when $m = 0$. Cassa & van Zyl (2014) suggested equations to predict m as a function of elasticity modulus (E), internal diameter (D), pipe thickness (t), longitudinal stresses (σ), and leakage length (l). Hence, Equation 4 predicts q through an interaction between C_d, A_0, and h, and an interaction between C_d, A_0, h, and m (and, consequently, E, D, t, σ, l). The experimental evidence suggests that, under some circumstances, Equations 2 and 4 remarkably improve the fitting of the leakage laws to the laboratory data with respect to Equation 1 (Ferrante et al., 2014).

Equations 1, 2 and 4 take into account the release of a liquid into the air, which is the case in this study, since our interest is for leaks in water distribution systems. For liquid leakages in another liquid (e.g. oil in seawater), other equations have been proposed in the literature, including geometrical factors such as leakage diameter, pipe thickness, leakage perimeter ratio, leakage inclination, and the presence (or absence) of grooves (e.g. Baptista et al., 2007). For leakages in gas-pipes, researchers have also suggested equations in order to predict q including factors such as leakage diameter and a material- and geometry dependent constant (Guo et al., 2007; Edrisi & Kam, 2013). Three-phase flow (water, oil and gas) in pipes with leaks were also investigated (Santos et al., 2014), however the authors did not suggest predictive equation for q. Although the equations proposed for liquids leaking in liquid and gas leaking in gas could not be used to estimate water leaking out through the leakage into the air, they could be used as a guide, and the independent variables considered in them could be used as a reference for this study.

Despite great efforts in previous studies on the discharge of water into air through leakages in pipes, the following aspects were not considered. Firstly, the main effect of factors like the mean flow velocity in the pipe (V) and the pipe thickness (t) was not considered in previous studies. Secondly, most of the studies used a one-factor-at-a-time experimental design strategy. In this strategy, design factors such as leakage area, leakage shape, pressure (or pressure head), etc., are analyzed by changing one factor at a time while holding the rest constant. The use of the one-factor-at-a-time strategy does not allow to estimate all two-factor and higher interactions between factors like leakage area, leakage form, pressure (or pressure head), etc. Surprisingly previous studies suggested equations that consider the interaction between factors, but they were not designed to discover the interaction between factors (e.g. Equations 1, 2, and 4). A thorough investigation of the effects of the main factors, along with their mutual interaction, is desirable for a better understanding of the subject. Finally, prior observational studies did not evaluate the relative importance of all the main factors and their interaction. Factorial design strategy is the only way to discover interactions between factors and to evaluate the relative importance of all the factors simultaneously with a smaller number of experiments (Berthouex & Brown, 2002). Baptista et al. (2007), for example, used successfully a factorial experimental design in order to investigate the importance and effects (main and interactions) of five geometrical factors of the leakage in submarine pipelines upon flowrate. However, their study was for oil leakages in seawater in which the seawater penetrates through the leakage, expulsing the oil, a phenomenon that is different from the interest of this study, since it involves two immiscible fluids and a phase inversion.

In order to address the issues mentioned above, computational experiments were conducted using a Computational Fluid Dynamics (CFD) tool that allows obtaining the leakage flow rate in a single leakage in a pressurized pipe. The goal was to determine the effects of leakage form (*F*), leakage area (*A*), pipe thickness (*t*), pressure (*P*), and mean velocity (*V*) on leakage flow rate (*q*) using a factorial experimental design strategy. The results provide insight into the main factors and their interaction and the relative importance of all the factors.

MATERIAL AND METHODS

Figure 1 shows a schematic representation of a pipe of a water distribution system used in this study. The leakage location is centered at the top of the middle of the pipe ($x = 0$, $y = D/2$, $z = 0$). The present calculations were conducted within the flow domain of a real pipe of diameter $D = 75$ mm and length of 2 m.

The set of experiments was done using a factorial design strategy to study the effects of all combinations of the leakage form (*F*), leakage area (*A*), pipe thickness (*t*), pressure (*P*), and mean velocity (*V*) on leakage flow rate (*q*). Each factor was investigated at two levels. Table 1 shows the factors and levels applied in the factorial design. The leakage form (circular and longitudinal) and leakage area (50 and 100 mm^2) levels correspond to typical values found in the literature (Greyvenstein, 2007). The longitudinal leakages had a length of 50 mm and 100 mm, respectively, and a width of 1 mm. We assumed that the area is constant (i.e. *A* is not a function of *h*) and $m = 0$ in Equation 3, i.e., our pipe material is inelastic (e.g. steel). Marchis & Milici (2019), for example, showed that the leakage area variation with the pressure (or head) can be neglected, depending on the pipe material and diameter. The range of velocity (0.6 and 3.5 m/s) and pressure (100 and 500 kPa) was chosen considering Brazilian regulations for water distribution systems (Associação Brasileira de Normas Técnicas, 2017). The range of pipe thickness (3.4 and 5.3 mm) was chosen considering the typical thickness of commercial PVC pipes. The statistical significance of each individual factor and their interactions at 95% significance level were evaluated.

Simulations were carried out using the commercial CFD (Computational Fluid Dynamics) code CFX®. This code uses the finite volume method for the spatial discretization of the domain. The governing equations are integrated over each control volume, such that mass and momentum are conserved, in a discrete sense, for each control volume. The simulations were performed using the RANS (Reynolds Averaged Navier Stokes) equations with a k–ε model.

The grid had finer spacing in regions of larger gradients (near the leakage and wall) and coarser spacing in the regions of low velocity gradients. The 3D mesh is a hexahedral mesh. A grid independency test was performed to ensure the quality of our CFD simulations. Three progressively finer grids were employed: a coarser grid, with 36,633 elements; a medium grid, with 49,212 elements; and a fine grid, with 223,148 elements, following procedures presented by Raad et al. (2008). More details of the grid independence study can be found in Silva et al. (2015). A grid with the same order of elements of the finest mesh was used in all simulations. The discretization error was on average around 2%.

Boundary conditions were defined at the borders of the computation domain. A uniform flow was imposed at the inlet, with streamwise velocity $u = V$ and cross-stream and transverse velocities equal zero ($v = w = 0$). At the leakage, the pressure was considered equal to the atmospheric condition, i.e. $P = P_{atm} = 0$ (gage). It is true that the leakage flow rate modeled in the absence of soils (outlet to atmospheric pressure), as assumed in our study and in most of the laboratory relations (Equations 1, 2, and 4) used in the computational models, may be higher compared to those of field conditions with the presence of soil (Latifi et al., 2018). Nevertheless, for high soil diffusibility (e.g. sand) the effect of soil upon the leakage flow rate is negligible (Noack & Ulanicki, 2008), as well as for high water pressure inside the pipe (Shahangian et al., 2019). At exit of the pipe, the pipe pressure at the outlet condition was considered. A no-slip boundary condition was applied at the walls.

The numerical model was validated using experimental measurements of Coetzer (2006). The simulations were conducted within the flow domain of a pipe of 110 mm diameter and 2-m

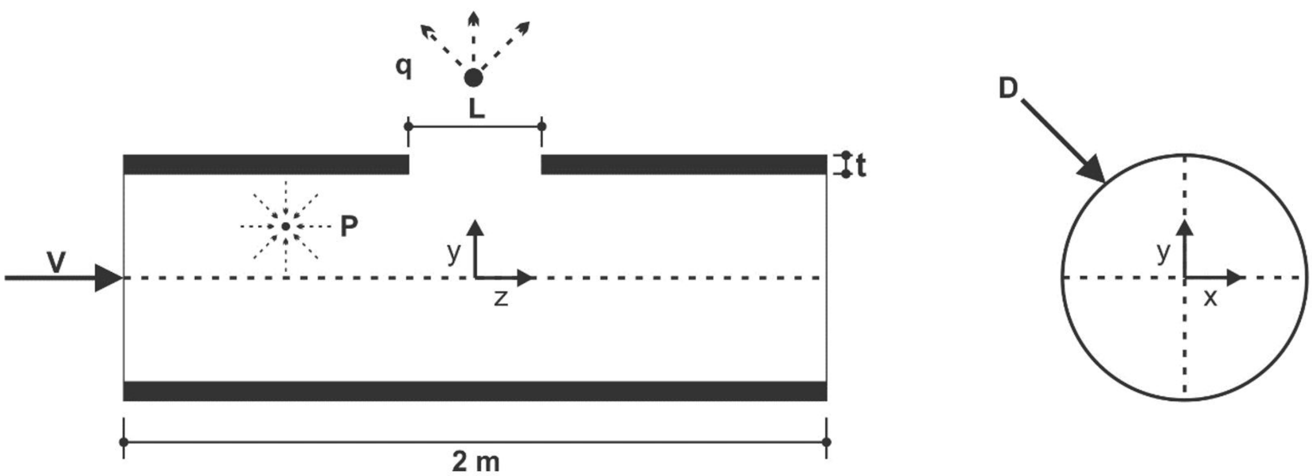

Figure 1. Definition sketch for a typical pipe of a water distribution system along the line $x = 0, y = D/2, z = 0$.

Table 1. Design matrix of the 2^5 factorial experimental design, levels of independent variables (*F*, *A*, *V*, *P*, and *t*) and observed response (*q*).

Experiment	*A* (mm²)	*F*	*t* (mm)	*P* (kPa)	*V* (m/s)	*q* (L/s)
1	50	C*	3.4	100	0.6	0.470
2	50	C	3.4	100	3.5	0.467
3	50	C	3.4	500	0.6	1.048
4	50	C	3.4	500	3.5	1.051
5	50	C	5.3	100	0.6	0.487
6	50	C	5.3	100	3.5	0.460
7	50	C	5.3	500	0.6	1.082
8	50	C	5.3	500	3.5	1.081
9	100	C	3.4	100	0.6	0.927
10	100	C	3.4	100	3.5	0.920
11	100	C	3.4	500	0.6	2.072
12	100	C	3.4	500	3.5	2.065
13	100	C	5.3	100	0.6	0.926
14	100	C	5.3	100	3.5	0.923
15	100	C	5.3	500	0.6	2.068
16	100	C	5.3	500	3.5	2.076
17	50	L**	3.4	100	0.6	0.580
18	50	L	3.4	100	3.5	0.577
19	50	L	3.4	500	0.6	1.295
20	50	L	3.4	500	3.5	1.295
21	50	L	5.3	100	0.6	0.581
22	50	L	5.3	100	3.5	0.574
23	50	L	5.3	500	0.6	1.304
24	50	L	5.3	500	3.5	1.295
25	100	L	3.4	100	0.6	1.165
26	100	L	3.4	100	3.5	1.161
27	100	L	3.4	500	0.6	2.608
28	100	L	3.4	500	3.5	2.602
29	100	L	5.3	100	0.6	1.163
30	100	L	5.3	100	3.5	1.155
31	100	L	5.3	500	0.6	2.608
32	100	L	5.3	500	3.5	2.598

long with imposed inflow velocity $V = 1$ ms^{-1}. The leakage hole had a circular shape ($L = d = 1$ mm) and was centered at the top of the middle section of the 2-m pipe ($x = 0$, $y = D/2$, $z = 0$). Leakage flow rate as a function of the pressure head showed that the maximum difference between numerical and experimental results was 7.1% (Figure 2).

RESULTS AND DISCUSSION

The Pareto chart (Figure 3) shows the relative importance of each of the factors, including their interaction up to the second order, upon the leakage flow rate (*q*). The main and interaction effects are the difference between the average response factors (*q*) at the high and low level, respectively, of the independent variables or their interactions (Montgomery & Runger, 2013). The vertical line in the chart indicates the minimum statistically significant effect magnitude for 95% confidence level. Any bars beyond the vertical line are statistically significant at the selected level of significance. Lenth's method was used to assess the significance of the main effects and the interaction effects in our unreplicated factorial experimental design (Lenth, 1989). In a decreasing sequence of relevance, the significant factors or combinations of them are: $P > A > A{\cdot}P > F > A{\cdot}F > FP$. The main effects of mean velocity and pipe thickness and their interaction on leakage flow rate are negligible.

Concerning the main effects (Figure 4a), change in pressure from low to high increased the flow rate through the leakage. The positive influence of the pressure upon leakage flow rate is well known (e.g. Walski et al., 2009). Reducing the pressure by half (from 500 kPa to 250 kPa) reduces leakage by 34% of the original rate. Pressure control is an efficient method to reduce leakage in water distribution systems. When leakage area increased, leakage flow rate also increased. This result is consistent with that reported by Greyvenstein (2007), Walski et al. (2009), and Paola & Giugni (2012). Reducing the leakage area by half (from 100 to 50 mm²) reduces leakage flowrate by 47%. Repairing and replacing leaking pipes is an important management procedure for water companies, particularly for large leakages (Macedo et al., 2018).

Leakage flow rate increased as the leakage opening changed from circular to longitudinal. This result should be a combination of flow contraction and viscous losses. The abrupt narrowing at the leakage produces a flow contraction called *vena contracta*. The bigger the flow contraction, the smaller is the leakage flow rate. Friction causes the velocity at the periphery of the *vena contracta* to be lower than that in the centre of the flow (Flachskampf et al., 1990). Since viscous friction happens at the jet perimeter, and the jet perimeter is greater for the longitudinal leakages (than the circular ones), the longitudinal leakages should present lower flow rates. This is well known from pipe flow, as explained by Flachskampf et al. (1990), where flow contraction does not happen and viscosity is the only limitation to flow. From pipe flow, a rectangular pipe would convey about 50% less water than a circular pipe of the same area (50 mm²), driving pressure, and friction factor (f = 0.011). Our results showed that the flow rate is approximately 20% larger in longitudinal (rectangular) leakages than in circular ones. This suggests that flow contraction dominates viscous effects, and that the flow contraction is smaller in longitudinal leakages than in circular ones, which is in agreement with the results obtained by Shao et al. (2019).

The main effect of t upon q is statistically insignificant. This is consistent with the results of Coetzer (2006) for leakages with $t/D < 2$. Although statistically insignificant, the increase of t also increased q. For circular leakages, smaller pipe diameters (1-12.7 mm), and pipe thickness-to-diameter ratios between 0.12 and 3.14, Rogers & Hersh (1976) observed that the flow rate is insensitive to t/D for $t/D < 0.4$, and that q increased with t/D for t/D between 0.4 and 1.0. This is consistent with our results, since our biggest t/D is 0.43.

Although the main effect of V upon q is statistically insignificant, change in velocity from low to high decreased the leakage flow rate, which is in agreement with the results of Araújo (2014) and Shao et al. (2019). As mentioned by Strakey & Talley (1999) and Shao et al. (2019), although the leakage velocity increases with the enhancement of the pipe velocity,

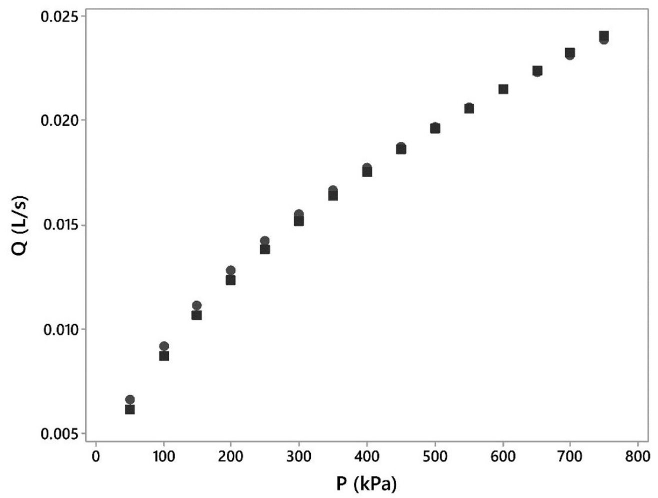

Figure 2. Comparison of the simulated leakage flow rate as a function of the pressure with the experiment of Coetzer (2006). Experimental: circles; computational: squares. V = 1 m/s, D = 110 mm, leak diameter = 1 mm. The maximum difference between numerical and experimental results was 7.1%. Coarse grid, with 36,633 elements (solid black lines); medium grid, with 49,212 elements (solid gray lines); fine grid, with 223,148 elements (dashed gray lines).

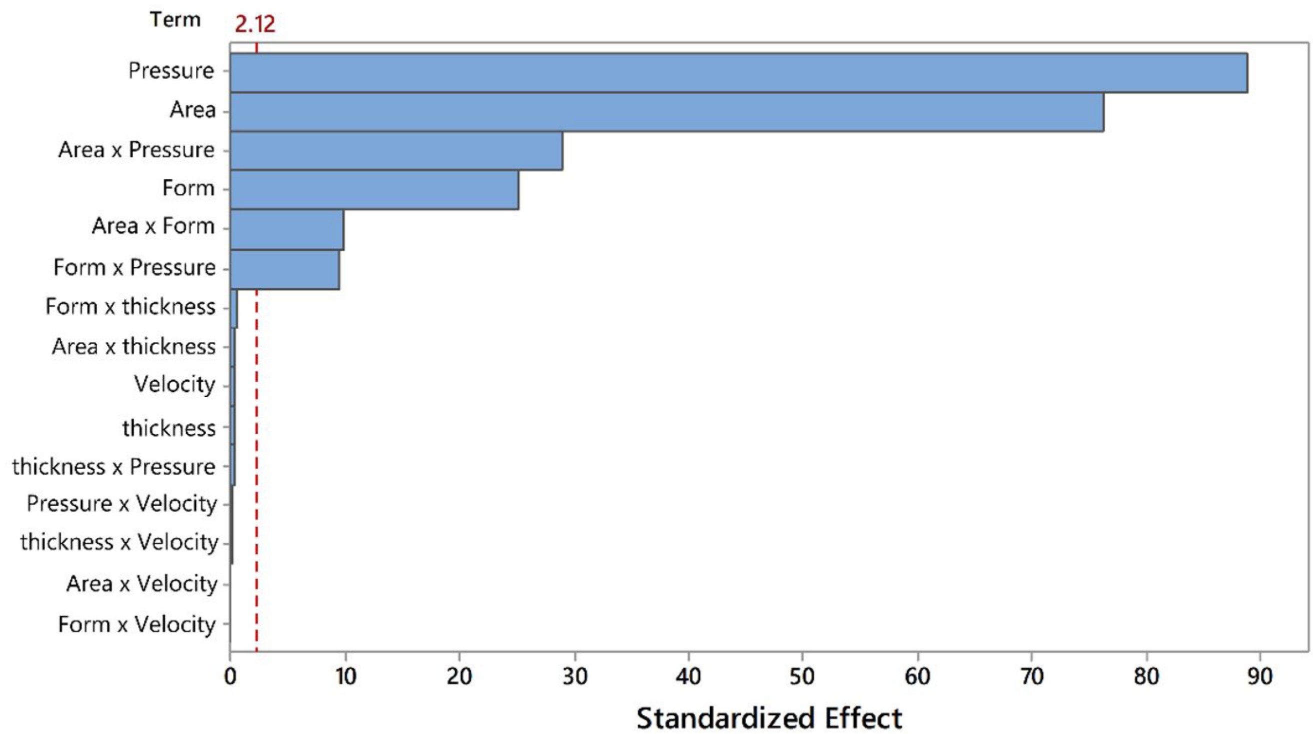

Figure 3. Standardized Pareto chart for q.

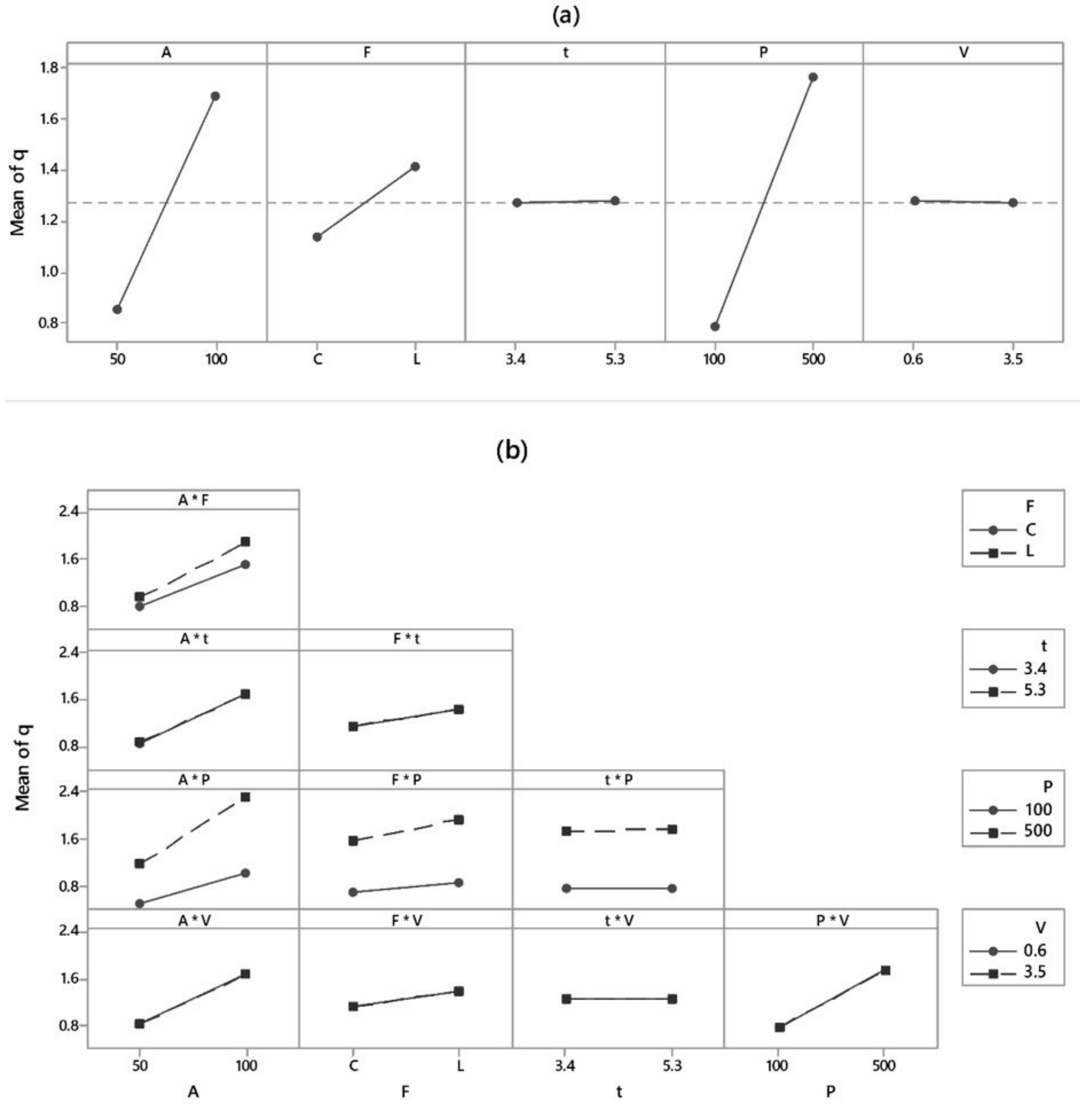

Figure 4. The main (a) and interaction effects (b) for *q*.

the contraction area of the outflow jet decreased, diminishing *q*, which means that the contraction of the jet has a greater effect on *q* than the leakage velocity.

With relation to the interactions (Figure 4b), the effect of pressure upon leakage flow rate is much stronger for a great leakage area than for a small leakage area. Although not mentioned in their paper, Walski et al. (2009) observed similar trends in terms of the interaction between pressure and leakage area. This higher leakage flow rates for bigger leakage sizes, as suggested by Ben-Mansour et al. (2012), may be because as the pipe pressure increases, the pressure difference across the leakage increases, and because the pressure loss across the leakage decreases as its size increases, increasing the pressure drop that causes the flow through the leakage. The effects of leakage area and pressure on leakage flow rate is more pronounced for longitudinal leakages than for circular leakages. It is important to observe that the interaction between pressure and leakage area that we observed is not the same as that described by Equation 4, since our pipe material is inelastic. For both pressures, the average leakage flow rate increased when the leakage form changed from circular to longitudinal, and the change in means for the lower pressure is smaller when compared to the change observed in the high pressure.

The literature provides little information regarding interaction effects between factors, since most of the investigators changed one factor at a time while holding the rest constant.

When we compare our results to Equations 1, 2 and 4, and consider that C_d is a constant, we observe that Equation 1 considered the effect of the interaction between A and P (pressure head, h), Equation 2 considered only the main effect of P (or pressure head, h), and Equation 4 considered the interaction between A and P (or pressure head, h), and the interaction between F (by including the leakage length to calculate m), t, and P (or pressure head, h). The other interactions and main effects were not considered important by the empirical equations. New "experiments" could be designed in order to find a new predictive model, using the factors, and their interactions, found to be significant. Two-level factorial experiments are not the best experimental design method to provide a regression model since they assume that the response and the factors are linearly related, which is not true (see, for example, Equations 1, 2, and 4). For accuracy, more complex experimental designs need to be employed.

This new predictive equation could furnish better results for the flow lost by a water distribution system than Equations 2 and 4. Boian et al. (2019), for example, compared Equations 2 and 4 to evaluate the leakage loss flow in urban water distribution systems. They concluded that the area of potentially detectable leakages ($A \geq 3.4$ mm^2), the interaction between the area of potentially detectable leakages and the pressure and the area of background leakages ($A < 3.4$ mm^2), are the factors that give the greatest difference between the flow loss by a water distribution system predicted by Equations 2 and 4. The study of Boian et al. (2019) suggests that a new predictive equation may be necessary to obtain predictions that are significantly different from that obtained by the equations already existing in the literature.

CONCLUSIONS

The pipe thickness and the mean velocity do not influence the leakage flow rate, while the pressure, leakage area and leakage form influence the leakage flow rate in a pressurized pipe. With relation to the interactions, the effect of pressure upon leakage flow rate depends on leakage area, being stronger for great leakage areas; the effects of leakage area and pressure on leakage flow rate is more pronounced for longitudinal leakages than for circular leakages. Based on our results, we suggest the revision of the predictive leakage flow rate equations found in the literature by carrying out new experiments, using the factors, and their interactions, found to be significant.

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