Leak behaviour in pressurized PVC pipes

M. Ferrante, C. Massari, B. Brunone and S. Meniconi

ABSTRACT

The correct definition of the leak law, i.e. the relationship between the leak outflow, the total head at the leak and other relevant parameters such as the pipe material, can seriously affect the accuracy of the numerical models used for the management of water distribution systems, either if they are used to forecast the leakage reduction by pressure management or to locate and size the leaks within an inverse analysis. In recent decades the use of the classical Torricelli or orifice equation has been questioned in the sense that some experimental results clearly demonstrated that the assumption of a leak outflow proportional to the square root of the head drop can yield unsatisfactory results. To investigate this behaviour, an experimental activity has been carried out at the Water Engineering Laboratory of the University of Perugia, Italy. Part of the results of the carried out tests are presented in this paper for a leak in a polyvinyl chloride (PVC) pipe. Leak laws based on the assumption of a leak area variation with the pressure are compared and validated by strain measures close to the leak.

Key words | leak, pressure control, PVC pipe, water distribution system

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INTRODUCTION

The relationship between leak outflow and pipe functioning conditions, or *leak law*, plays a crucial role in water distribution system management. Numerical simulations of pressurized pipe networks (Giustolisi *et al.* 2008; Giustolisi & Laucelli 2011), leakage control by pressure reduction techniques and leak sizing and location by means of transients (e.g. Brunone 1999; Brunone & Ferrante 2001; Brunone *et al.* 2008; Ferrante *et al.* 2009; Meniconi *et al.* 2011), all rely on a proper definition of this relationship.

As mentioned in Lambert (2001), the basic hydraulic relationship could be derived by considering a mean velocity at the leak given by Torricelli's velocity expression:

$$V_T = \sqrt{2gH} \quad (1)$$

In Equation (1) the total head of the flow in the pipe upstream of the leak, H, can be replaced by the piezometric head, h, when the velocity head is negligible. Both H and h are referred to as the leak elevation, under the assumption that the leak discharges into the atmosphere. While the derivation of this relationship for the steady-state flow from an orifice in the thin wall at the bottom of a tank is quite simple, its extension to the leak in the wall of a pipe is not trivial. Nevertheless, the leak discharge is often evaluated as:

$$Q_L = A_E V_T = A_E \sqrt{2gH} \quad (2)$$

where the leak outflow, Q_L, is expressed as the product of V_T and the leak effective area $A_E = C_L A_L$, with C_L and A_L being the discharge coefficient and the leak area, respectively.

Under some circumstances the effective area can vary with H (May 1994; Walski *et al.* 2006; Greyvenstein & van Zyl 2007; Cassa *et al.* 2010) depending on the pipe material and thickness (Ferrante *et al.* 2011; Ferrante 2012; Massari *et al.* 2012). To broaden to such cases the use of Torricelli's formula, a power law has been introduced by the IWA Water Loss Task Force (e.g. Thornton 2003), here expressed as:

$$Q_L = a_I H^{b_I} \quad (3)$$

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which includes Equation (2) when $a_I = a_T = A_E(2g)^{1/2}$ and $b_I = 1/2$. In a different way, May (1994) and Cassa *et al.* (2010) introduced a linear dependence of A_E on H:

$$A_E = A_{EO} + m\mathrm{H} \tag{4}$$

in Equation (2) yielding:

$$Q_L = A_{EO}\sqrt{2gH} + m\sqrt{2g\mathrm{H}^3} = a_c H^{1/2} + b_c H^{3/2} \tag{5}$$

To explore the relationships given by Equations (3) and (5), some tests were carried out at the Water Engineering Laboratory of the University of Perugia, Italy.

EXPERIMENTAL SETUP

The tests were carried out on a system with a high density polyethylene (HDPE) pipe DN110 PN10, 16.7 m long, with an internal diameter 93.3 mm and a wall thickness 8.1 mm (Figure 1). The pump (P) supplied the needed discharge to the upstream air vessel (AV) from the recycling reservoir (R). At the downstream end section of the pipe, there was a hand-operated ball valve (DV) discharging into the air. An automatically controlled butterfly valve (MV) was placed immediately upstream of DV. A longitudinal leak (L) of 90 × 2 mm with rounded edges was machined in the middle of a DN 110 PN 16 unplasticized polyvinyl chloride (PVC) trunk, with a thickness of 6.6 mm and a length of 1,050 mm, placed at about 11.5 m from the AV (Figure 1). The geometry of the leak as well as the trunk length and diameter are the same as those considered in similar tests carried out on a steel pipe (Ferrante 2012), on a HDPE pipe (Massari *et al.* 2012) and on an oriented PVC pipe (Ferrante *et al.* 2012).

Two electromagnetic flowmeters were used to measure the discharge upstream (UD) and downstream (DD) of the leak, with an accuracy of 0.2% of the measured value. Two piezoresistive pressure transducers, with a 7 bar full scale (f.s.) and an accuracy of 0.1% f.s., measured the pressure upstream (UP) and downstream of the leak (DP). A differential pressure transducer was used to verify that the difference between the pressures at UP and DP was less than the accuracy of the used instruments. The flow and pressure signals were acquired for 100 minutes at a 10 Hz sampling rate and down-sampled to 1/10 Hz for the first test. For the second test, with a duration of 2 days, the signals acquired at 1 Hz were down-sampled to 1/60 Hz. The total head, H, was evaluated by the pressure and the discharge measured upstream of the leak. Strain gauges were also placed at the middle of the leak to measure the radial strain in the pipe. More details about the same setup in the same functioning conditions are provided in Ferrante *et al.* (2013).

RESULTS AND DISCUSSION

In the first test, the automatically controlled butterfly valve MV was manoeuvred with the UV and DV valves fully open. Figure 2 shows the time-history of the total head, H,

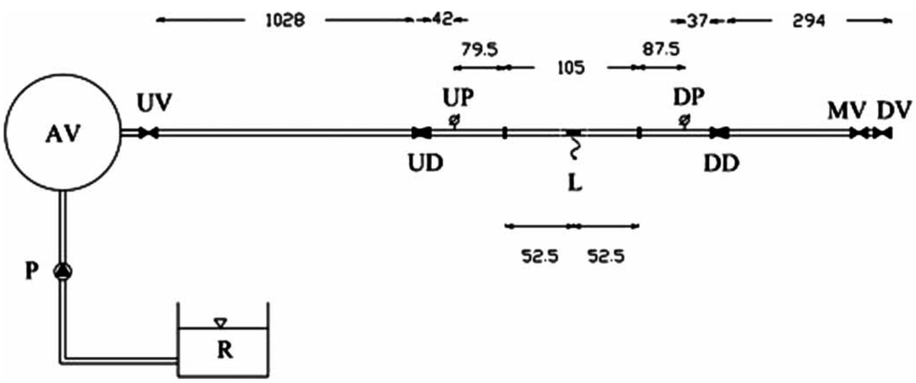

Figure 1 | Layout of the experimental setup. R = recycling reservoir; P = pump; AV = air vessel; UD (DD) = upstream (downstream) flowmeter; UP (DP)= upstream (downstream) pressure transducer; L = leak; MV = butterfly valve; UV (DV) = upstream (downstream) valve. Measures are in centimetres.

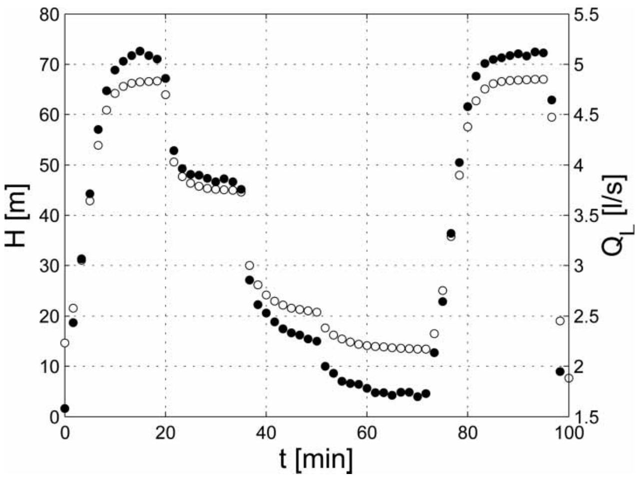

Figure 2 | Time-history of the total head, *H*, (○) and leak discharge, Q_L, (●) during the first test.

(hollow circles) and leak discharge, Q_L, (filled circles) while Figure 3 shows the same data in the (H, Q_L) domain. In Figure 3 the fittings of the data by Torricelli's equation with a constant $a_T = A_E(2g)^{1/2}$ and by Equations (5) and (3) are also shown.

The fitting by Torricelli's equation seems to demonstrate that this model does not adequately simulate the data. Although the value of $R^2 = 0.94$ shows that the experimental data are not far from the fitting curve, the residuals are strongly correlated to H. That is, the fitting overestimates (underestimates) the data for low (high) values of H. This behaviour can seriously affect the extrapolation outside the range of the measured data. Furthermore, the value of the estimated effective area is $1.31 \times 10^{-4}\,m^2$ and is larger than $1.22 \times 10^{-4}\,m^2$, which is the area of the machined leak. Hence, this value yields a discharge coefficient larger than one if a leak area larger than the machined one is not considered.

The value of $R^2 = 0.998$ associated with the fitting by Equation (3) confirms that relaxing the constrain on the H exponent yields an improvement in the model performance so that the correlation between residuals and H disappears. The estimated exponent is $b_I = 0.69 > 0.5$ and the value of $a_I = 2.84 \times 10^{-4}$ cannot be directly linked to the leak effective area.

The fitting by Equation (5) has the same R^2 value of the fitting by Equation (3) and the differences between the two models are not appreciable in statistical terms. The

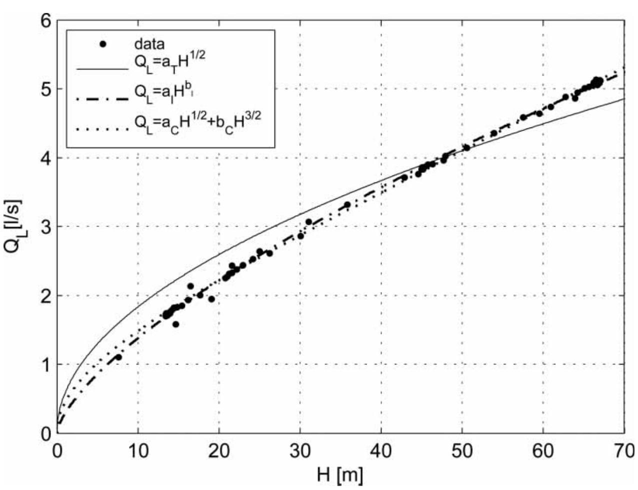

Figure 3 | Variation of the leak discharge, Q_L, with the total head, *H*, for data of Figure 2.

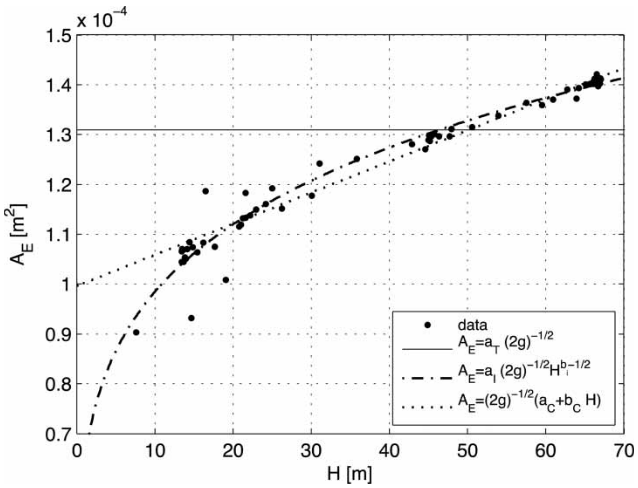

Figure 4 | Variation of the leak effective area , A_E, with the head, *H*, for data of Figure 2.

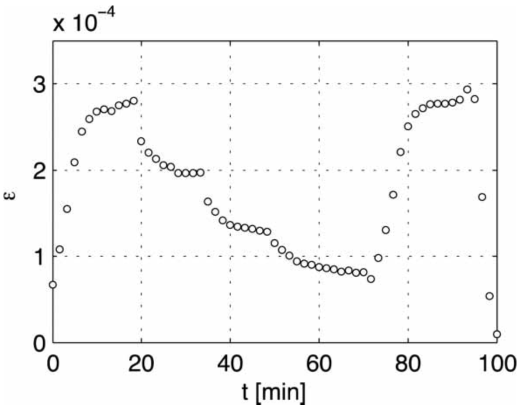

Figure 5 | The time-history of the radial strain close to the leak, ε.

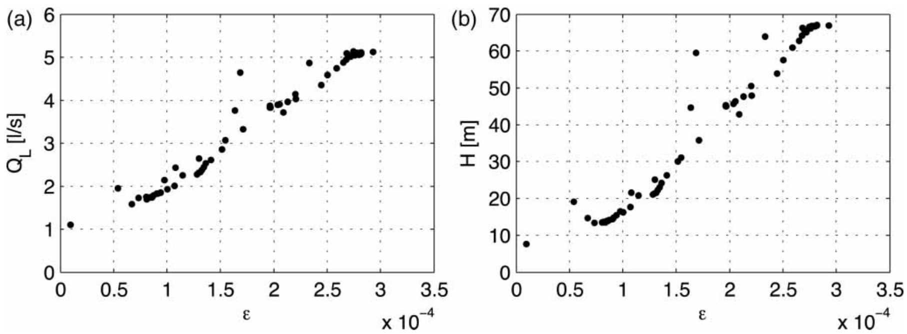

Figure 6 | Variation with the radial strain at the leak, ε, of the total head, H, (a) and of the leak discharge, QL, (b).

estimated value of the a_C coefficient gives a leak effective area corresponding to 1.00×10^{-4} m^2 which is compatible with the machined area and a discharge coefficient of 0.82.

Since both Equations (3) and (5) fit the data better than the classical Torricelli equation with a constant effective leak area, the possible variation of this parameter with H is investigated. As a first step, in Figure 4 the estimated values of $A_E = Q_L/(2gH)^{1/2}$ are shown (filled circles). The experimental data contradict the choice of a constant value of A_E (solid line) and suggest a dependence on H. Both the fitting curves obtained by Equations (3) and (5) are also proposed in Figure 4 (dot-dashed and dashed line, respectively). The value of b_C $=2.767 \times 10^{-6}$ yields a slope of the fitting line $m = 6.247 \times 10^{-7}$; this value is similar to those obtained by Cassa *et al*. (2010) for longitudinal leaks in PVC pipes.

To understand if this behaviour is related to the leak area deformation, the radial strains at the leak, ε, have been acquired during the test (Figure 5). The strain data are clearly correlated to Q_L and H as shown in Figure 6. This result suggests that the leak discharge depends on the leak area deformation and that this deformation depends on the total head inside the pipe. Figure 7 confirms this finding since the variation in the estimated leak effective area is strongly correlated with the variation of the radial strains at the leak.

During the second test, the pipe functioning conditions were varied to reproduce the effects of a typical demand pattern in time (Figure 8). The results of the actual functioning conditions on the dependence of Q_L and A_E on H are shown in Figures 9 and 10, respectively, where the fittings with the same functions of Figure 3 are also shown. In spite of the

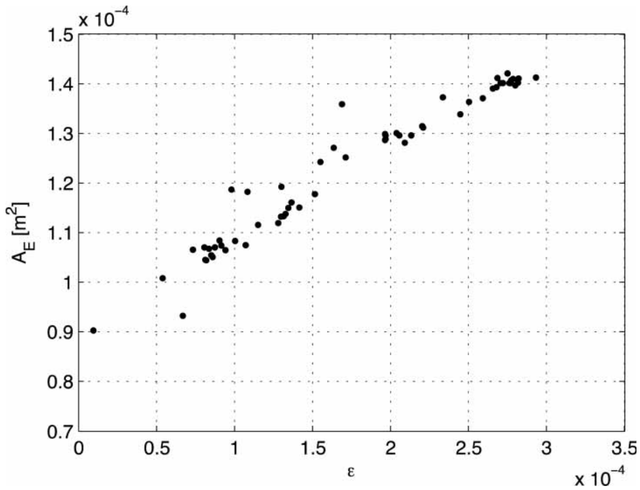

Figure 7 | Variation of the leak effective area, A_E, with the radial strain at the leak, ε.

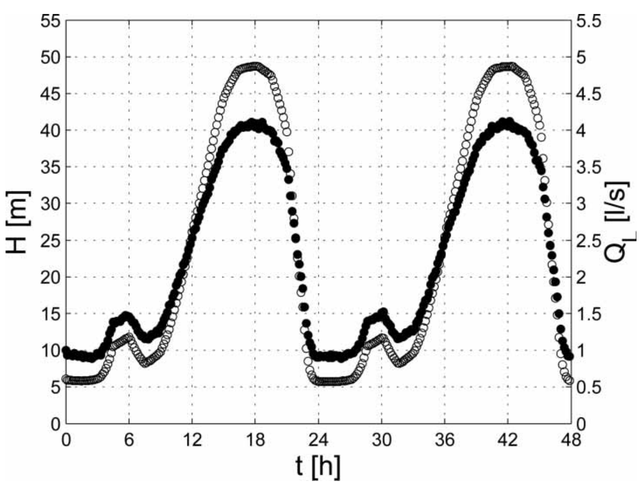

Figure 8 | Variation in time of the head, H, (○) and of the leak discharge, Q_L, (●) for a realistic demand pattern (second test).

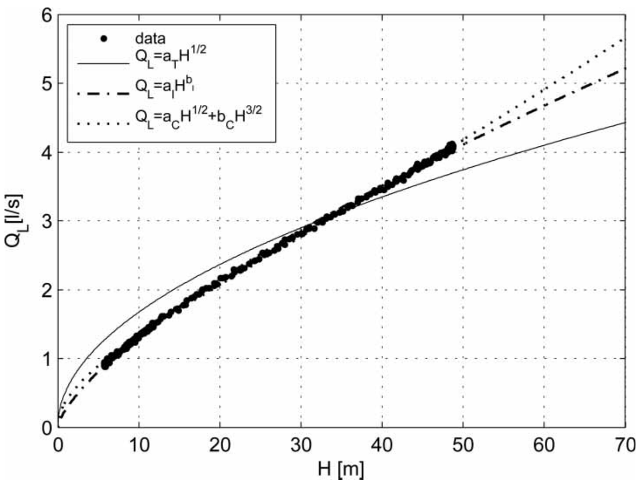

Figure 9 | Variation of the leak discharge, Q_L, with the total head, H, for data of Figure 8.

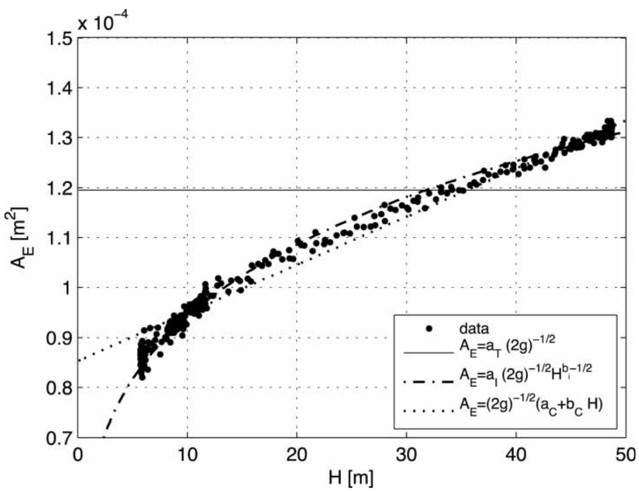

Figure 10 | Variation of the leak effective area , A_E, with the total head, H, for data of Figure 8.

potential PVC viscoelastic behaviour, the time effects on the data coming from different days are not relevant. The same applies to the A_{E} variation with H shown in Figure 10, which basically confirms the results of Figure 4.

CONCLUSIONS

In this paper, results are shown for tests carried out at the Water Engineering Laboratory of the University of Perugia, Italy, on an unplasticized PVC pipe with a leak. The measured leak outflow is related to the total head in the pipe by means of the classical Torricelli (or orifice) equation, assuming a constant leak effective area, and two relationships which also consider a possible variation of the leak effective area with the pipe functioning conditions. Both the latter equations perform better than the former in the fitting of the experimental data, suggesting that the effective area variation with the total head cannot be neglected. The assumption of a linear functional dependence between these quantities improves significantly the fitting. The linear variation of the leak effective area with the total head is corroborated by the radial strain measures in the pipe at the leak.

Previous tests carried out using the same experimental setup showed that leaks in a pipe of plastic materials can present a hysteretical and time-dependent relationship between leakage and total head, typical of the viscoelastic behaviour (Ferrante *et al*. 2011; Massari *et al*. 2012). Although PVC is a plastic material, the viscoelastic effects are not evident for the 2 day test.

The shown results contribute to the experimental analysis of the leak hydraulic characterization with particular reference to the pipe material effects. Further contributions are needed to define in a proper manner the dependence of the leakage on other relevant parameters.

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