LEAKAGE AND PIPE MATERIALS

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Abstract

The water distribution systems management often requires the definition of the relationship between leak outflow and flow conditions inside the pipe. To explore this relationship, several tests were carried out at the Water Engineering Laboratory of the University of Perugia (Italy). To analyze the leak outflow dependence on functioning conditions for different pipe materials, leaks with the same geometry were machined on steel and polyethylene pipes. The results of the test on the polyethylene pipe confirm the viscoelastic behavior of the leaks in these pipes, i.e. the leakage dependence on the functioning conditions time-history. On the contrary, the tests in the steel pipes of different thickness seem to confirm an elastic or elastoplastic behavior of the leaks. Since the considered test conditions are similar to those of functioning systems, it seems reasonable that the shown effects of the material properties on the leakage, especially for polyethylene pipes, can be relevant for water distribution systems management.

Keywords
Leakage, Water distribution systems, Viscoelasticity, Plastic pipes, Pressure.

1. INTRODUCTION

The relationship between leak outflow and pipe functioning conditions plays a crucial role in water distribution systems simulations. Based on literature, the leak outflow, Q_L, depends mainly on the leak effective area $C_L A_L$ – defined as the product of the discharge coefficient C_L and of the leak area A_L – and on the total head inside the pipe, H, or on the piezometric head, h. Other quantities can also be considered, as pipe thickness, discharge conditions (in air/submerged), ratio Q_L/Q_U (with Q_U being the discharge upstream the leak), and, for large leaks, leak shape (Greyvenstein and van Zyl 2007; Osterwalder and Wirth 1985; van Zyl and Clayton 2007).

In steady-state conditions the general equation

$$Q_L = aH^b \tag{1}$$

is often used (Greyvenstein and van Zyl 2007; Lambert and Thornton 2005) that includes the Torricelli's equation

$$Q_L = C_L A_L \sqrt{2gH} \tag{2}$$

when $a=C_L A_L (2g)^{1/2}$ and b=1/2.

Eq. (1) is used both at a global/district area scale, with H being a "mean pressure" over the district and Q_L is the flow entering the district, and at a local scale, considering a single leak. In both cases, on a local as well as on a global scale, the variation of $C_L A_L$ with H can be used to explain the increase of the b exponent with respect to Torricelli's formula (May 1994; van Zyl and Clayton 2007).

Cassa et al. (in print) show that for an elastic pipe the increase in the leak area depends linearly on *h* and hence propose the relationship

$$Q_L = ch^{0.5} + dh^{1.5} \tag{3}$$

where $c = C_L A_0 \sqrt{2g}$, $d = C_L m \sqrt{2g}$ with A_0 is the leak area for *h*=0, and *m* is a parameter.

The use of the pressure head, *h*, instead of *H* in both Eqs. (1) and (2) is equivalent for practical applications and in the considered tests, since the kinetic head is negligible when compared to the total head. Although our choice does not affect the shown results, based on our measurements we prefer to use *H* when a relationship with *Q* is analyzed. To explore this relationship on a local scale, tests were carried out at the Water Engineering Laboratory of the University of Perugia (Italy). Different pipe materials and thicknesses were considered. Eqs. (1), (2) and (3) are applied on a local scale, considering a single leak discharging into the atmosphere. Since the variation in time of the flow conditions were very slow, the results can be considered as coming from succeeding steady states.

2. EXPERIMENTAL SET-UP

Tests were carried out on a high density polyethylene pipe DN110 PN10, about 20 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 DV. For the shown tests, three trunks were used: two steel trunks, both of 105 cm length, with a thickness of 1.5 and 0.5 mm (SA and SB, respectively) and a high density polyethylene trunk of 115 cm and a thickness of 8.1 mm (PE). The Young modulus is E_A=2.1 10^{11} Pa for the steel trunks and E_P=1.9 10^9 Pa for the polyethylene trunk. The trunks had the same internal diameter of 93.3 mm. A longitudinal leak (L) of the same geometry (90x2mm) was machined in the middle of each trunk as reported in Figure 1. During some preliminary tests (not shown) the leak on SB reached a yielding stress and changed its geometry due to a plastic deformation.

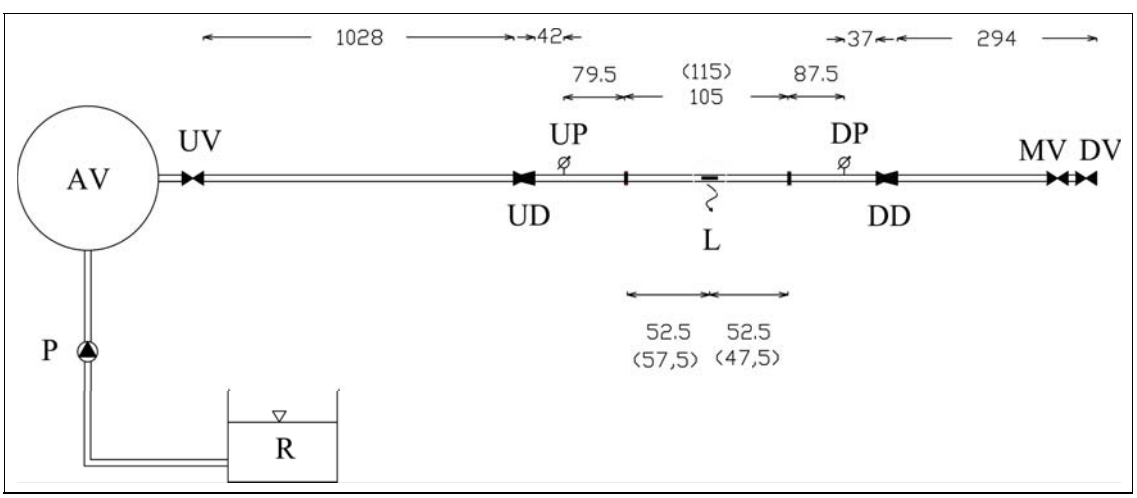

Figure 1. Layout of the experimental set-up. R = recycling reservoir; P = pump; AV = air vessel; UD (DD) = upstream (downstream) flowmeter; UP (DP) = upstream (downstream) pressure transducer; L = leak; MV = butterfly valve; UV (DV) = upstream (downstream) valve. The measures are in centimeters. The measures inside brackets refer to the PE trunk.

Two electromagnetic flowmeters were used to measure the discharge upstream (UD) and downstream (DD) the leak, with an accuracy of 0.05% 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 the leak (DP).

Flow and pressure signals were acquired at a 1 Hz sampling frequency, filtered by means of Wavelet DB2 filter to reduce the noise effect (Ferrante et al. 2007; Ferrante et al. 2009a) and down-sampled to 1/60 Hz to simplify representation. The total head, H, is evaluated from the horizontal plane through the leak, with the pressure head measured at the transducer UP and using the kinetic head corresponding to the upstream measured discharge. Note that in the considered cases this last term could be neglected.

3. EXPERIMENTAL RESULTS

Tests were carried out using the automatically controlled butterfly valve MV and with the UV and DV valves fully open. The same maneuver was repeated, with the same time-history of the valve opening degree, for the three considered trunks, simulating the typical daily demand and head variation in a functioning system during a day. Two demand flow peaks were simulated, the first, larger, around 7:00 and the other, smaller, around 18:00, corresponding to the two minima of H. The same cycle of valve maneuvers was repeated for three days, although only the last two days are shown in the figures. Because of both the length and the wave speed of the laboratory pipe, the order of magnitude of the water hammer characteristic time is 10^{-1} s. As a consequence, considering the durations of the closure and opening maneuvers, much larger than such a characteristic time, the inertial effects can be neglected and in the shown tests the system can be regarded as passing through a sequence of steady states. Figure 2 shows the time-history of the total head, H, for the carried out tests. The corresponding measured values of the leak discharge, Q_L, are reported in Figure 3.

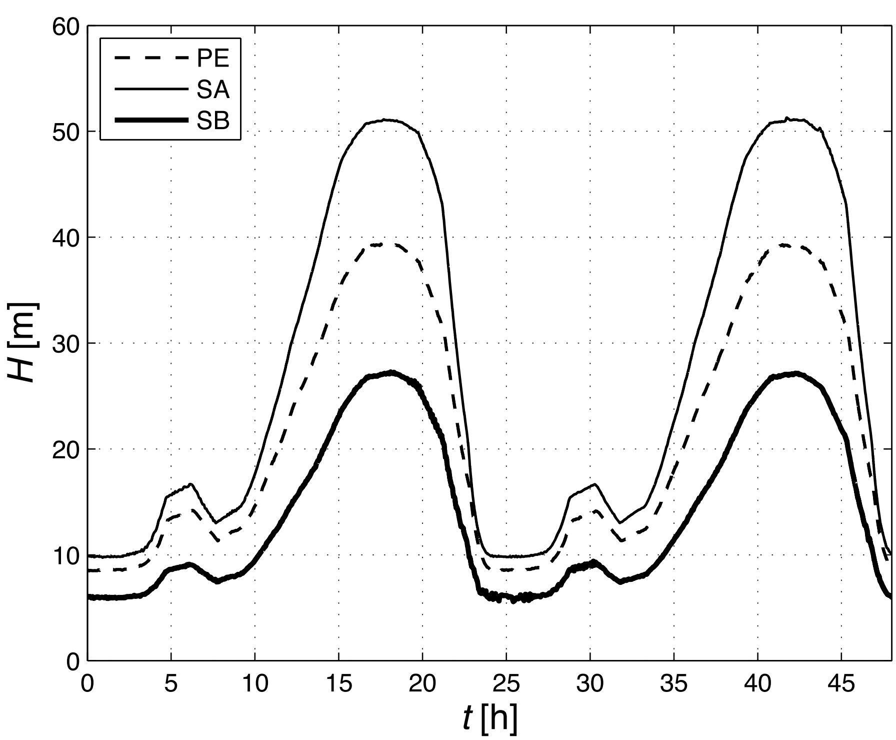

Figure 2. Time-history of the upstream total head, H for the carried out tests.

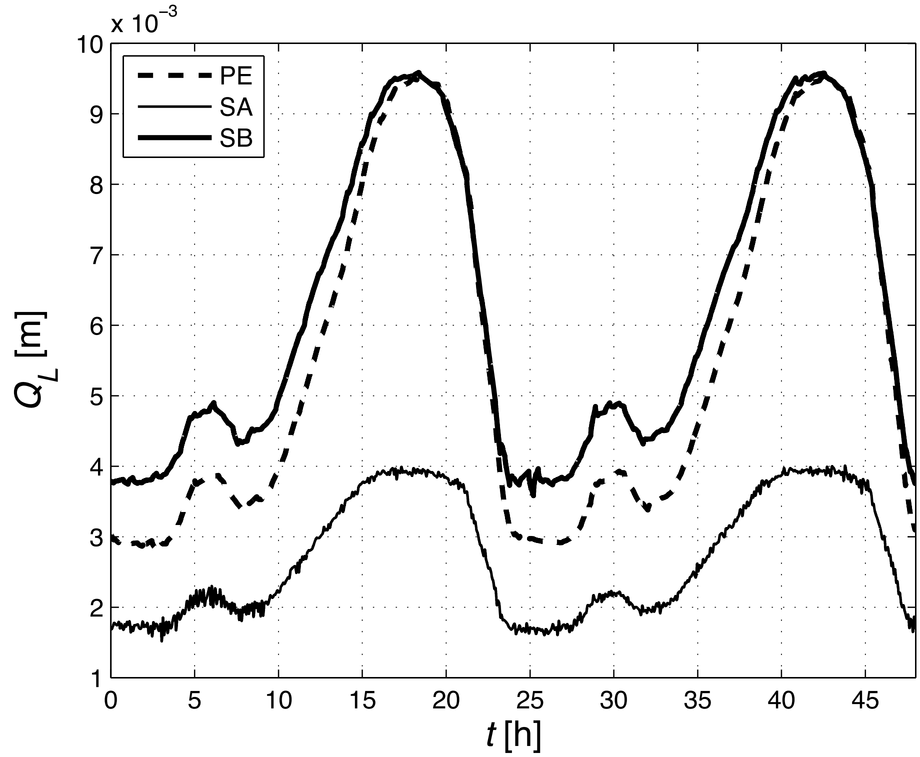

Figure 3. Time-history of the leak discharge, Q_L, for the carried out tests.

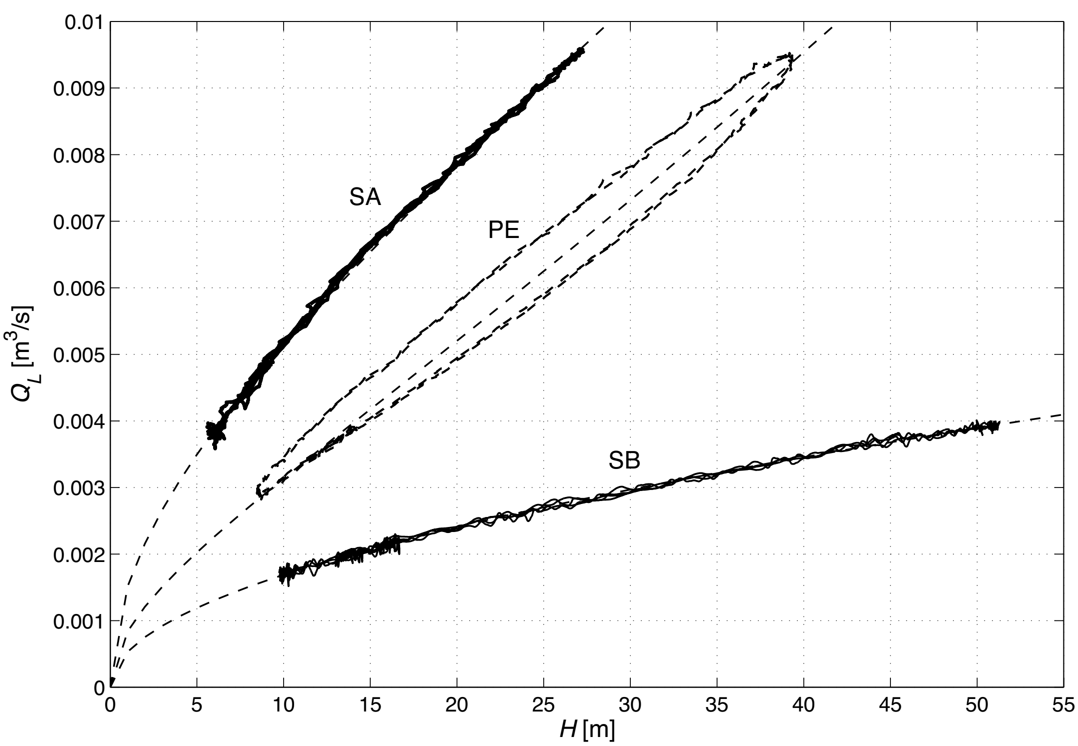

Figure 4. Data of Figs 3 and 4 in the (H,Q_L) domain. The dashed curves represent the fitting by Eq. (2).

Nevertheless the considered leaks have the same machined geometry, the assumption of a single relationship for the considered trunks cannot explain the differences in the head and flow variation in time. To explore the different behavior of the three trunks, the data of Figures 2 and 3 are plotted in the (H,Q_L) domain (Figure 4). As can be seen, three different relationships of the Q_L=Q_L(H) law can be derived.

For the steel SA pipe, with a 1.5 mm thickness, the fitting with the Eq. (1) gives quite satisfactory results with a = 5.098 10^{-4} m^{-b} and b = 0.5192. Since b is very close to 1/2, we can conclude that the leak in this case obeys to the Torricelli's law of Eq. (2). Actually, the a value is equal to the theoretical one if C_L= 0.643. The fitting of the same data by Eq. (3) confirms that the elastic enlargement of the leak due to the pressure is negligible; in fact, d = 4.117 10^{-7} $m^{-3/2}$ and the second term in Eq. (3) expressing the leak outflow due to the elastic deformation of the leak caused by h, explains only the 3.7% of the total discharge for H=50 m. The two fittings, i.e. by Eqs. (1) and (3), produce two almost coincident curves.

The leak machined geometry of the steel pipe SB, with a thickness of 0.5 mm, is equal to that machined on SA. Nevertheless, the relationship fitted on the data on trunk SA cannot be applied, with the same a and b values, on these data, since the relationship is clearly different. The fitting on the SB data yields a = 1.265 10^{-3} m^{-b} and b = 0.6116. These values suggests that the Torricelli's equation does not apply since b>1/2. The fitting by Eq. (3) is also performed, assuming that the deviation from the Torricelli's law can be due to the elastic deformation of the leak geometry and hence to the leak area dependence on the pressure. When compared with the SA results, the fitting produces larger values of c and d (c = 1.499 10^{-3} $m^{-1/2}$ and d = 1.260 10^{-5} $m^{-3/2}$). The increase in the d value with respect to the SA trunk, related to the elastic enlargement of the leak area, is associated to the smaller thickness and hence with the larger strains in the pipe. The value of c can be explained considering that during a preliminary test (not shown), an increase of the pressure head up to 28 m caused a permanent leak deformation, due to a plastic strain. The increase in the leak area was appreciable even by naked eye. The measured enlarged area at the beginning of the shown test was of about 4.61 10^{-4} mm^2; assuming this value for the leak area it is C_L = 0.734 .

A completely different behavior is obtained when data from the PE trunk are shown in the same (H,Q_L) representation of Figure 4. Instead of a single curve, these data follow two curves: in the first part of the day, when H and Q_L increase in time, they describe the lower and convex curve of the cycle, while in the last part of the day, when H and Q_L decrease, they describe the concave and higher part. The data measured during the 2 hours following the local maxima at t = 6 and 30 h remain on the lowest part of the cycle, although H and Q_L decrease. In the two days, the synchronous H and Q_L couples describe the same closed curve.

A fitting of the whole set by means of a single equation as (1), (2) or (3) does not yield satisfactory results since none of these equations is able to represent the hysteresis cycle. In some papers (Ferrante et al. 2009b; Ferrante et al. 2010) the relationship of these curves with the pressure time history is explored, suggesting a link between the polyethylene viscoelastic properties and the leak head-discharge relationship. Based on the shown results on the steel pipes, this suggestion can be extended to a more general dependence of the leak hydraulic behavior on the pipe material.

4. CONCLUSIONS

The shown results clearly demonstrate that the relationship between leak outflow and pipe functioning conditions can depend on the pipe material. For small and circular leaks, where the area can be considered as not depending of the head inside the pipe, the Torricelli's law still gives satisfactory results (e.g.: Greyvenstein and van Zyl 2007). On the contrary, when the combination of pipe radial stiffness and leak size and shape produces appreciable deformations in the leak area, the pipe material can affect the dependence of Q_L on H. Basing on the shown results, the rheologic properties of the pipe material (i.e. elastic, elastoplastic or viscoelastic) produces different relationships between Q_L and H nevertheless leaks with the same area are machined on trunks with the same inner diameter. This effect is noticeable for PE pipes with a hysteretical cycle, related to demand and head variations. Since the considered pipe geometry and test conditions are similar to those of functioning systems, a possible dependence of the leakage on the pressure time-history cannot be excluded in water distribution systems, although further studies are needed.

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