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Procedia Engineering 162 (2016) 455 – 462

Procedia Engineering

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International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016

Pressure reducing valve characterization for pipe system management

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Abstract

Pressure control strategy through Pressure Reducing Valves (PRVs) has been deeply investigated as management strategy, aimed at water leakage reduction avoiding very expensive pipe replacement programmes. On the contrary, few experimental data are available in literature, particularly in unsteady-state conditions. In this paper, the results of some tests carried out at the Water Engineering Laboratory of the University of Perugia (I) in order to characterize a PRV with two set points for high and low pressures are presented. The PRV is installed in a single high-density polyethylene (HDPE) pipe supplied by a tank in which the pressure is assured by pumps of different characteristics. Two types of tests are considered: steady-state tests, to characterize the PRV, and extended period tests, to check its dynamic behaviour.

Peer-review under responsibility of the organizing committee of the EWaS2 International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development

Keywords: Pressure reducing valve; Leakage; Pressurised pipes; Extended period simulation

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Peer-review under responsibility of the organizing committee of the EWaS2 International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development
doi:10.1016/j.proeng.2016.11.088

1. Introduction

A significant reduction of background leakages and pipe bursts is the necessary condition for improving efficiency and performance of water distribution systems (WDS). Towards such an aim, a consolidated approach envisions pipe system sectorization by establishing District Metered Areas (DMAs) to control both pressure and flow regime. In fact in such smaller hydraulically isolated sub-systems – obtained by dividing the WDS into a number of discrete areas by closing some boundary valves – the volumes of water entering and leaving can be measured as well as the analysis of the pressure regime is facilitated. Further, DMAs are often supplied through a Pressure Reducing Valve (PRV) to control the inlet pressure. When fixed set-point PRVs are installed, the possibly high varying upstream pressure is reduced to a quite stable and smaller downstream value compatible with the minimum one as required to satisfy the users' demand. Criteria for the optimal design of DMAs and PRVs location – for which many contributions are offered in literature, e.g., [1] and [2], to cite two of the most recent – are beyond the scope of this paper where attention is focused on the analysis of the behaviour of PRVs both in steady and unsteady-state conditions. This research – based on the results of tests executed at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy – is motivated by the lack of a clear experimental evidence about the actual response of PRVs to the highly variable flow and pressure regimes experienced by WDS. Moreover, literature shows that some aspects need further analysis. In [3] and [4], as an example, several dynamic models to represent the behaviour of PRVs are examined and their performance assessed. The instability phenomena for low flows (small valve opening) are investigated in [5] where the importance of the gain (i.e., the ratio between the change in the PRV outlet pressure in steady-state against the change in the valve opening) is pointed out. It is worthy of remarking that the unwanted interaction between PRVs and network transients may give rise to both quality problems and large pressure peaks. In [6], the effects of demand changes in terms of the generation of pressure oscillations are examined and more reliable PRV controllers are proposed. Unsteady-state tests carried out in [7] and [8] in a real pipe system show that: i) persistent red water phenomena may be caused by pressure surge due to the action of a PRV, and ii) the actual flow-rate curve of the PRV can be evaluated by measuring the pressure signal upstream and downstream of it during transient tests.

This paper shows the results of an extensive experimental campaign carried out at WEL and is an extension of [9], in which the effect of fast transients – due to water demand sudden increase and decrease – on a PRV is studied. The system under investigation consists of a high-density polyethylene (HDPE) pipe where a pressure reducing valve is installed. Flow variations are generated by manoeuvring an automatically controlled butterfly valve. At the PRV inlet, the pressure is modified by using different pumps to supply the upstream tank. The main aims of this paper are: (i) to characterize the PRV by means of steady-state tests, and (ii) to check its dynamic behaviour during extended period tests.

2. Experimental setup

The HDPE laboratory pipe at WEL has an internal diameter of D = 93.3 mm (a nominal diameter DN110), and a total length of L = 199.30 m (Fig. 1). The pipe is supplied by a tank, T, in which the pressure is assured by means of two pumps whose shutoff heads are $H_{T,Q=0}$ = 22 m and $H_{T,Q=0}$ = 55 m, respectively. In the downstream end section of the pipe, a controlled motorized butterfly valve (MV), with a nominal diameter DN80, is placed. A pressure reducing valve (PRV) with a nominal diameter DN80 is installed at a distance L_1 = 129.59 m downstream of the supply tank (Fig. 2). The PRV is a double stage pressure reducing valve; during tests, the high pressure set point is disconnected and the low pressure set point is fixed at 5, 10 and 26 m, respectively. Pressure signals, H, are acquired by piezoresistive transducers with a frequency acquisition of 100 Hz at: section V, placed immediately upstream of the end valve, section D, at a distance of 0.78 m downstream of the PRV, section U, at a distance of 0.79 m upstream of the PRV, as well as at the supply tank, T. The discharge, Q, and the minor head loss across the PRV, ζ, is measured by means of a magnetic flow meter at a distance of 23.78 m from the tank, and a variable reluctance differential pressure transducer, respectively. Finally, the relative opening degree of the PRV, δ, is measured by means of an electronic valve position indicator.

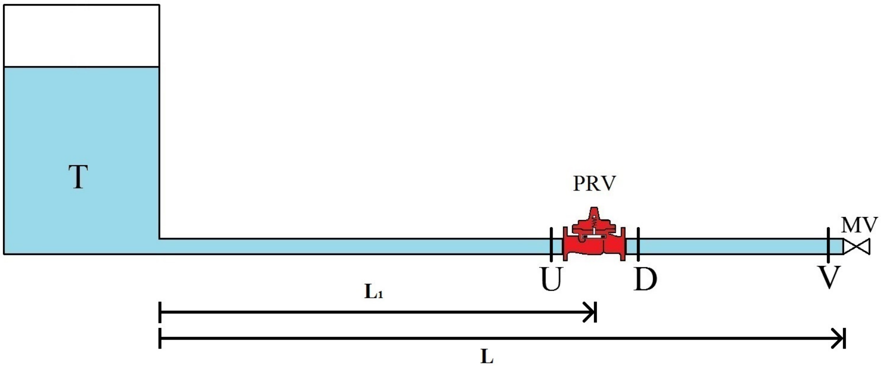

Fig. 1. Sketch of the experimental setup (T = supply tank; U = section immediately upstream of the PRV; D = section immediately downstream of the PRV; V = section immediately upstream of the MV; MV= manoeuvre valve).

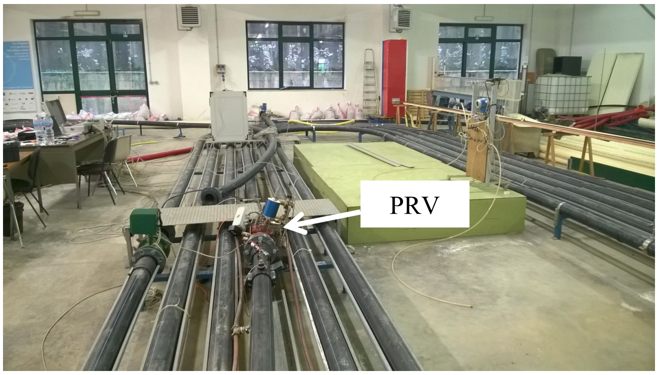

Fig. 2. The pressure reducing valve and the experimental pipe at the Water Engineering Laboratory of the University of Perugia.

3. Hydraulic characterization of the PRV

Steady-state tests were carried out to determine the hydraulic characteristics of the PRV: the minor head loss ζ was measured for different values of δ ($\delta = 0$ % for fully closed valve and 100 % for fully open valve), and Q. According to the usual flow regime in real pipe systems, the experiments concerned turbulent flow, and for any given relative opening degree, the value of the minor head loss coefficient, χ, was determined through the following equation:

$$\zeta = \chi \frac{Q^2}{2gA^2} \qquad (1)$$

where g = gravity acceleration, and A = pipe area.

Fig. 3 shows the relationship between the experimental values of χ and δ, along with the power interpolation law:

$$\chi = a\delta^b \qquad (2)$$

by a continuous line. The values of the empirical coefficients are $a = 1.9529*10^8$, and $b = -3.401$ and the corresponding coefficient of determination, R^2, is equal to 0.985. The main differences between the interpolated curve and the experimental data are evident at the small relative openings, according to findings of [8].

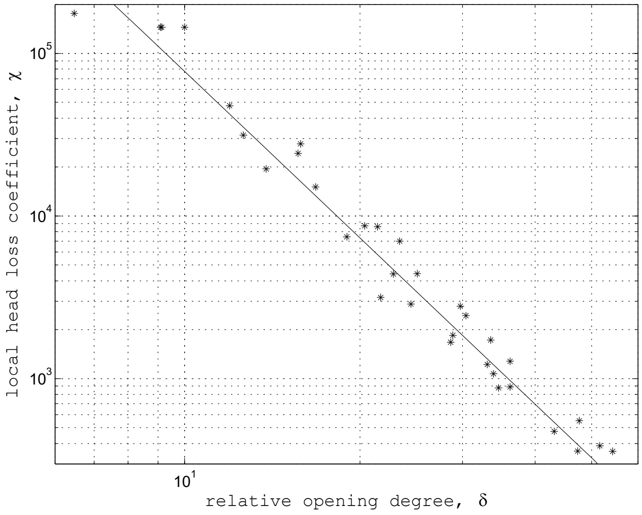

Fig. 3. PRV hydraulic characterization: experimental and interpolated values of χ vs. δ.

Since the PRV is not a partially closed in-line valve with a fixed value of the opening degree, but the self-adjusting PRV opening, and consequently the pressure head loss across it, depends on the conditions at the inlet and the nominal downstream set-point (hereafter referred to as nominal set-point), Fig. 3 plot is not sufficient to completely characterize such a valve. Further information about the hydraulic behaviour of the PRV are given in Fig. 4 where the experimental values of χ are reported vs. the Reynolds number, *Re* = *QD*/*A*ν (where ν = kinematic viscosity of the fluid), for different conditions at the PRV inlet and outlet. For given inlet and outlet conditions, χ decreases with increasing *Re*; in fact the pressure at the inlet decreases and, for a fixed outlet set-point, the local head loss thorough the PRV decreases.

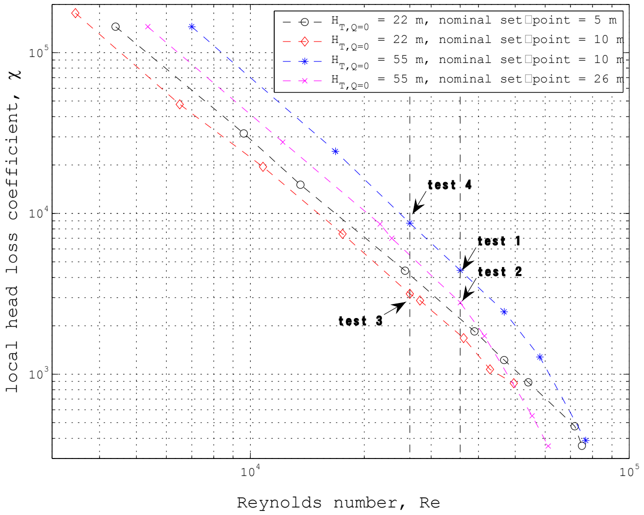

Fig. 4. Minor head loss coefficient, χ, as a function of *Re* for given values of the outlet nominal set-point and shut-off heads at the tank (further information about the highlighted tests are given in Fig. 5).

To better understand the experimental behaviour of the PRV for a given *Re* but different inlet and outlet conditions – i.e., different values of H_U and H_D, respectively – Fig. 5 shows the hydraulic grade line for tests 1, 2, 3, and 4 reported in Fig. 4. Precisely, Fig. 5(a) shows two tests, with the same *Re* (= 3.6*10^4) and inlet PRV condition (H_U = 46.0 m) but a different downstream set-point (for test 1: $H_{D,1}$ = 10.8 m, and for test 2 $H_{D,2}$ = 26.5 m, with the second subscript indicating the test number). These values constrain the PRV to be more closed for test 1; in other words, χ_1 (= 4425) is larger than χ_2 (= 2786) and δ_1 (= 23.2 %) is smaller than δ_2 (= 26.6 %). Fig. 5(b) reports two tests, with the same *Re* (= 2.6*10^4) and outlet PRV condition (H_D is equal to about 10.1 m) but a different inlet condition ($H_{U,3}$ = 21.6 m < $H_{U,4}$ = 48.4 m). As a consequence, the PRV has been automatically settled to a larger opening degree for test 3 (δ_3 = 25.6 % > δ_4 = 19.0 %, and χ_3 = 3156 < χ_4 = 8726).

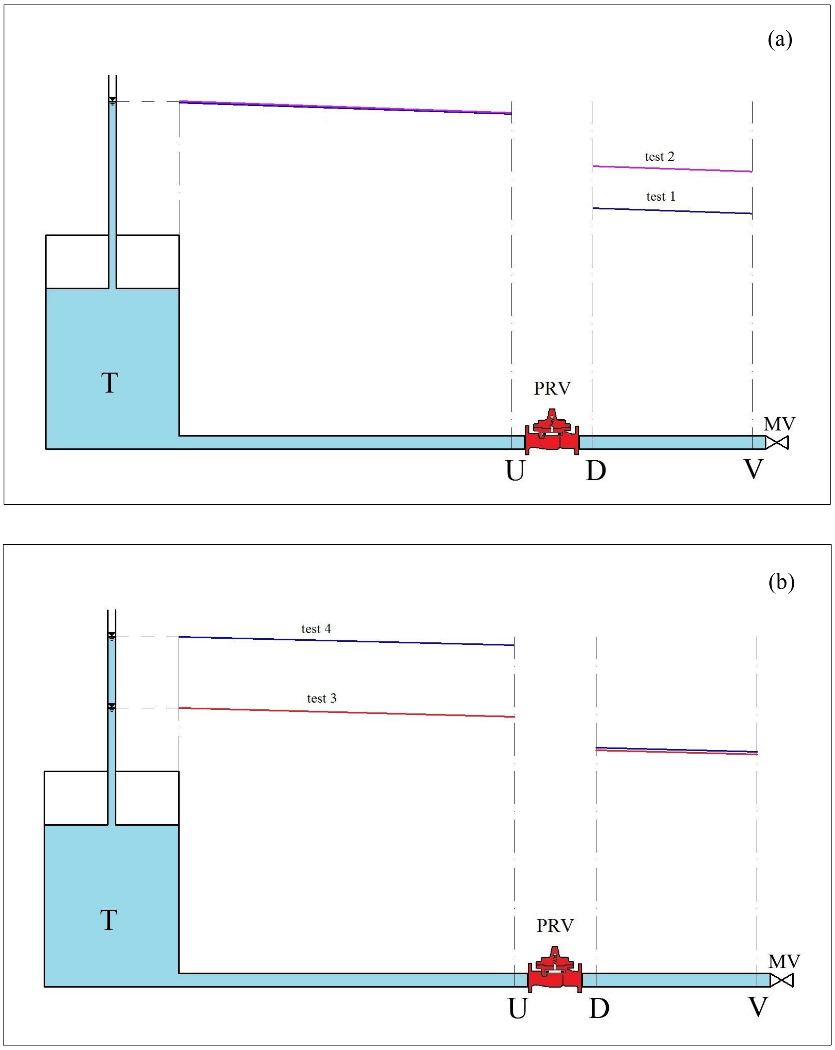

Fig. 5. Hydraulic grade line in steady-state condition with the sketch of the experimental setup for: (a) tests 1 and 2; (b) tests 3 and 4 of Fig. 4.

It is worthy of noting that a small difference occurs between the value of the nominal set point and the measured PRV outlet pressure; moreover no valuable effect of *Re* can be noticed. As shown in Fig. 6, the maximum value of such a difference is equal to about 2.6 m and, consequently, it has no effect when such a device is used in real pipe systems.

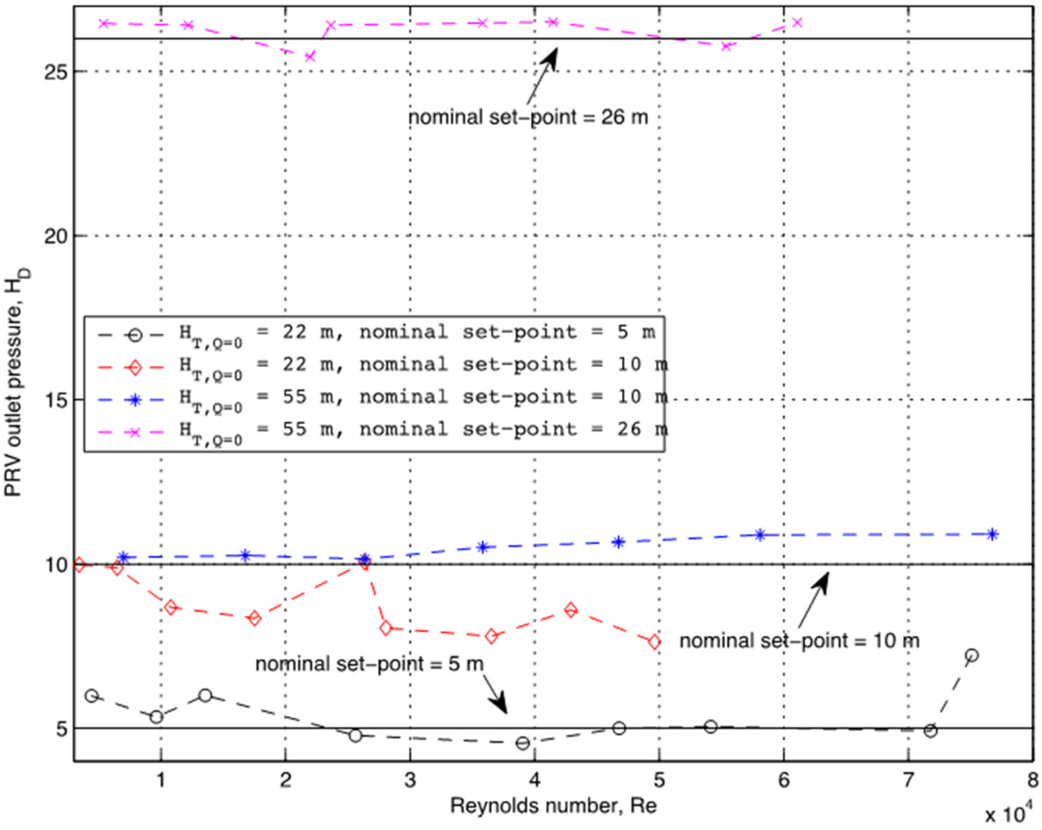

Fig. 6. PRV outlet pressure, H_D, vs. the Reynolds number, *Re*.

The flow conditions inside the pipe have been changed by means of the automatic controlled valve. Because of the length and wave speed of the laboratory pipe, the order of magnitude of the pipe characteristic time, τ, is 10^{-1} s. As a consequence, considering that the duration of the closure and opening manoeuvres is much larger than τ, the inertial effects can be neglected, and in the executed tests, the system can be regarded as passing through a sequence of steady states. Using the language of the pressurized pipe network modellers, this condition is typical of an extended period simulation (EPS).

The feature of the executed EPS simulates an extended period (i.e., 12 hours) with pump and tank controls – the pump with a shutoff head $H_{T,Q=0}$ = 55 m is used – and a typical demand pattern of real-world pipe systems with specified changes at designated times. Particularly, two peaks of demands are imposed: about at the 4th hour and 9th hour, respectively. In Figs. 7(a), 7(b), and 7(c) the variation in time of H_V, H_D, and H_U, Q, and δ are reported, respectively. As expected, the PRV opening (Fig. 7c) is directly proportional to the discharge variation (Fig. 7b). In the time period far away from the demand variations, while the inlet pressure, H_U, changes accordingly to the pump characteristics curve – it diminishes with increasing discharge – the outlet pressure, H_D, is about constant (its value is around the nominal set-point). However, the manoeuvre of MV modifies the values of H_U and H_D not negligibly. To look at these variations into more details, in Fig. 8 two magnified visions of Fig.7 are reported in the time interval when the largest demand decrease (Figs. 8a-8c) and increase (Figs. 8d-8f) takes place, respectively.

In both cases, the larger pressure variations take place at sections downstream of the PRV, whereas smaller pressure changes occur at section U, because of the action of the PRV that almost isolates the upstream branch of the pipe (Figs. 7a and 7d).

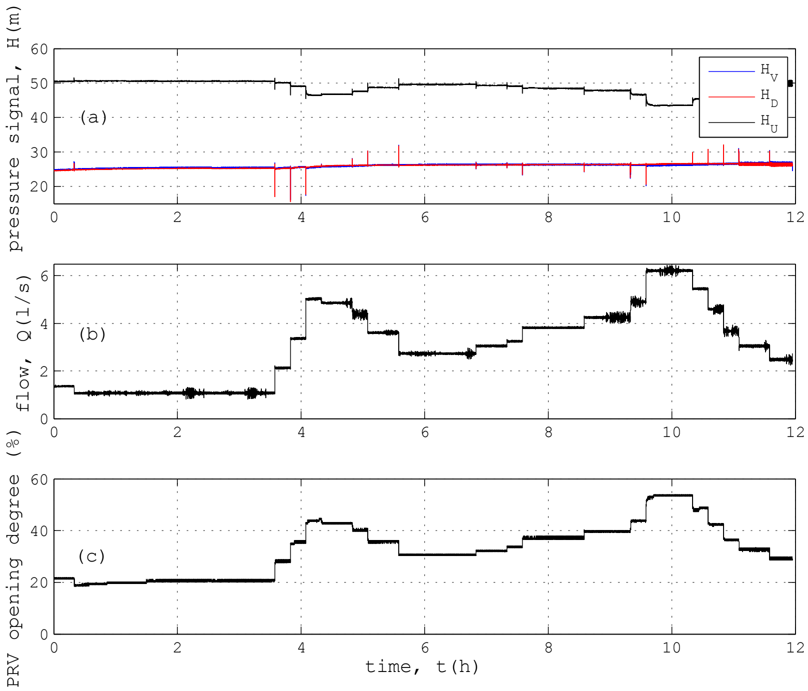

Fig. 7. Variation in time of (a) H_V, H_D, H_U, (b) Q, and (c) δ.

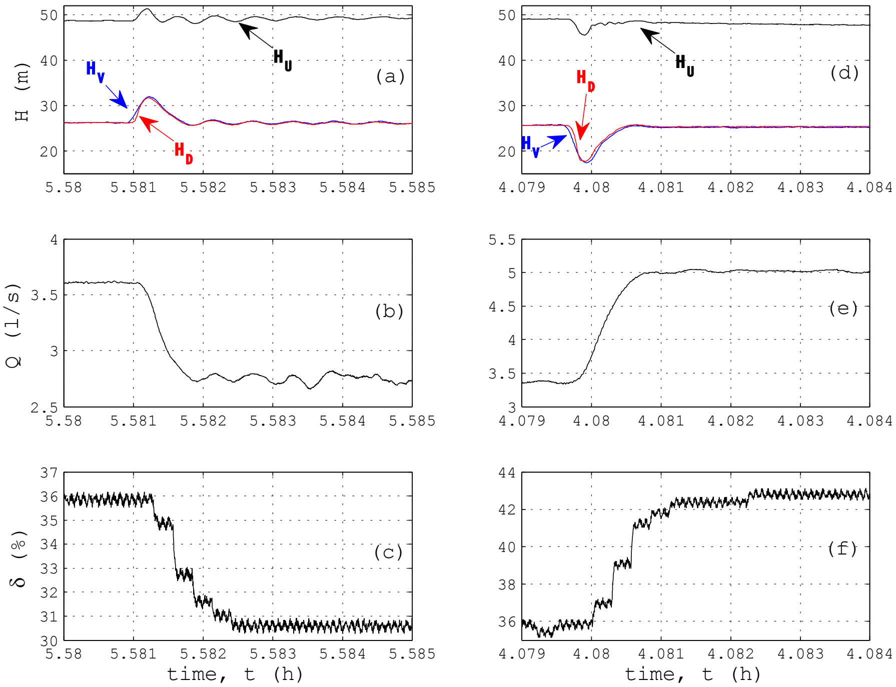

Fig. 8. Magnified vision of Fig. 7 in the time interval when the largest demand decrease (a-c), and increase (d-f) takes place, respectively.

4. Conclusions

Despite the important role that pressure reducing valves (PRVs) play in pipe system management – as a powerful tool for pressure control – in literature there is a lack about their actual behaviour both in steady- and unsteady-state conditions. In this paper laboratory tests have been executed to characterize the hydraulic behaviour of the PRV by evaluating the steady-state local head loss for different relative opening degrees and turbulent flow. Moreover, since the PRV is not a partially closed in-line valve with a fixed value of the opening degree but a self-adjusting valve, the effect on its hydraulic behaviour of both the inlet pressure and downstream set-point has been explored. Long period tests – similar to the extended period simulations of pipe system modellers – have been carried out to check the behaviour of the PRV when a typical demand pattern is considered. These tests have confirmed the possibility of fixing the downstream pressure value around the nominal set-point. Furthermore, pressure oscillations due to the manoeuvres take place for a short period of time downstream of the PRV, whereas no significant propagation occurs upstream.

Acknowledgements

This research has been supported jointly by the University of Perugia, the Italian Ministry of Education, University and Research (MIUR) — under the Projects of Relevant National Interest “Advanced analysis tools for the management of water losses in urban aqueducts” and “Tools and procedures for an advanced and sustainable management of water distribution systems” — and Fondazione Cassa Risparmio Perugia, under the project “Hydraulic and microbiological combined approach towards water quality control (no. 2015.0383.021)”.

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