Hydraulic characterization and transient response of pressure reducing valves: laboratory experiments

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ABSTRACT

A pressure reducing valve (PRV) regulates the outlet pressure regardless of the fluctuating flow and varying inlet pressure, thereby reducing leakage and mitigating the stress on the downstream water distribution network (WDN). Notwithstanding the crucial importance of PRVs, few experimental data are available in the literature. The aim of this paper is to overcome this gap by means of the results of a large number of tests carried out at the Water Engineering Laboratory of the University of Perugia, Italy. These tests have been executed on a standard type of PRV in steady-state conditions, to characterize it, and in unsteady-state conditions, to check its transient response. A broad range of laboratory conditions simulating possible events in WDNs has been examined and both short and long duration monitoring have been carried out. The analysis of the tests demonstrates the versatility of PRVs as a powerful tool for pressure management, and also when the flow condition changes according to the users' demand pattern. In fact, their transient response is appropriate with small pressure oscillations generated by the PRV self-adjustment. Moreover, proper PRV modelling has to include both its mechanical behaviour and the characteristics of the pressure pipe system in which it is installed.

Key words | hydraulic characterization, leakage reduction, pressure control, pressure reducing valve, transient response

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INTRODUCTION

Complex topology and quite unpredictable users' demand of water distribution networks (WDNs) make it difficult to fulfil the requested functioning conditions. Particularly, within ordinary strategies to reduce leakage, there is the need for keeping the pressure at a given value downstream of some selected nodes. In fact, it often happens that, because of a reduction of the demand, the pressure exceeds the value in line with the discharge to be supplied downstream. As a consequence, an undesired increase of water losses takes place in the downstream part of the WDN. Instead of repairing pipe breaks – often time consuming and costly to detect and locate – leakage is managed by controlling the pressure regime by means of pressure reducing valves (PRVs). Such devices are hydraulically controlled and allow setting of the downstream pressure at a desired value (hereafter referred to as nominal set-point, H_{NSP}, with $H =$ piezometric head). When the upstream pressure exceeds H_{NSP}, a partial closure of the PRV automatically happens and the local head loss through it increases.

Since PRVs control pressure by fully-automatic self-adjusting of their opening degree, and they do not require any type of external power source, they are installed throughout the world. Notwithstanding their crucial importance in the management of WDNs, a very narrow body of literature with an exhaustive experimental check of their actual behaviour is available. In fact, the literature is rich in contributions about the optimal location of PRVs in WDNs, as an example within the design of District Metered

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Areas (e.g., Vairavamoorthy & Lumbers 1998; Araujo *et al.* 2006; Liberatore & Sechi 2009; Nicolini & Zovatto 2009; Ali 2015; Creaco & Pezzinga 2015a, 2015b; Sivakumar & Prasad 2015; Covelli *et al.* 2016). Moreover, most of the scarce literature on the actual behaviour of PRVs is focused on their dynamic modelling and possible instability (e.g., Simpson 1999; Prescott & Ulanicki 2003, 2008; AbdelMeguid *et al.* 2011; Ulanicki & Skworcow 2014; Ulanicki *et al.* 2015), transients generated by their action (e.g., Meniconi *et al.* 2015a), and the related negative effects in terms of water quality (Brunone & Morelli 1999; Karney & Brunone 1999). As a result, there is a need for analysing the performance of PRVs with regard to some very important features from the management point of view: (i) fulfilment of H_{NSP} for different values of the upstream pressure, (ii) response to fast/slow demand changes, and (iii) role of the pipe system configuration.

The purpose of this paper is to verify how well a PRV – in particular the one manufactured by Donald G. Griswold, the inventor of this kind of device in 1936 – maintains a fixed and specified downstream pressure under a range of rapidly and slowly changing flow conditions in a pipe system. Specifically, the aim is to fill some of the gaps in the PRV characterization with regard to both steady- and unsteady-state behaviour by means of the experiments executed at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy. In such tests, the PRV is installed in a high-density polyethylene (HDPE) pipe, where different system configurations and demand patterns are simulated to check its performance; demand changes are carried out by manoeuvring an automatically controlled valve or by pump trip and start up.

This paper is an extension of the one presented at the 2nd edition of the International Conference on 'Efficient & Sustainable Water Systems Management toward Worth Living Development – EWaS2016' (Meniconi *et al.* 2016).

EXPERIMENTAL SETUP

The HDPE laboratory pipe at WEL has an internal diameter of $D = 93.3$ mm, a nominal diameter DN110, and a wall thickness equal to 8.1 mm (Figure 1). The pipe is supplied by a pressurized tank (T) in which the head is assured by means of two pumps whose shutoff heads are $H_{T,Q=0} = 22$ m and $H_{T,Q=0} = 55$ m ($Q =$ discharge), respectively. In the downstream end section of the pipe, an automatically controlled motorized butterfly valve (MV), with DN80, is placed.

A PRV (Figure 2) with DN80 is installed at a distance $L_1 = 129.6$ m downstream of T; to check the role played by the system configuration, during tests, two values of the length of the pipe downstream of the PRV, L_2, have been considered (=69.7 m and 181.8 m, with $L = L_1 + L_2$ being the total length).

In Figure 3, a schematic of the PRV, with the main valve and the pilot control system, is reported. The main valve is hydraulically operated and diaphragm-actuated. It is controlled by the pilot (CP), in which H_{NSP} is set by adjusting the compression of a spring placed above the CP diaphragm. When the pressure at section O exceeds H_{NSP}, CP closes, and the flow from section I towards the cover chamber actuates the diaphragm of the main valve which closes. Otherwise, when pressure at the outlet section O is smaller

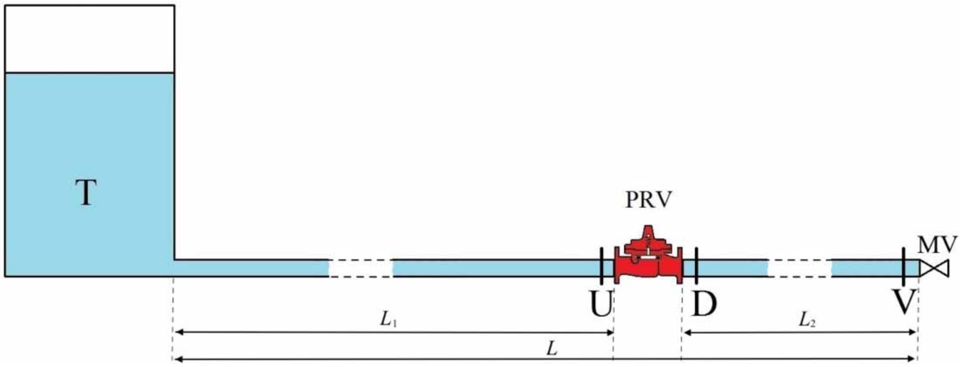

Figure 1 | Sketch of the experimental setup (T = supply tank; PRV = pressure reducing valve; MV = manoeuvre valve; pressure measurement sections: U = upstream of the PRV; D = downstream of the PRV; V upstream of the MV).

Figure 2 | The experimental pipe and the PRV (in the insert) at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy.

than H_{NSP}, CP opens, allowing the flow from the inlet section I to section O, through the strainer-orifice assembly (SOA). Such a pressure reduction downstream of the SOA lets a flow from the cover chamber to the SOA take place. This flow actuates the diaphragm of the main valve, which opens. The opening/closing speed of the main valve is set by means of the control valves CV.

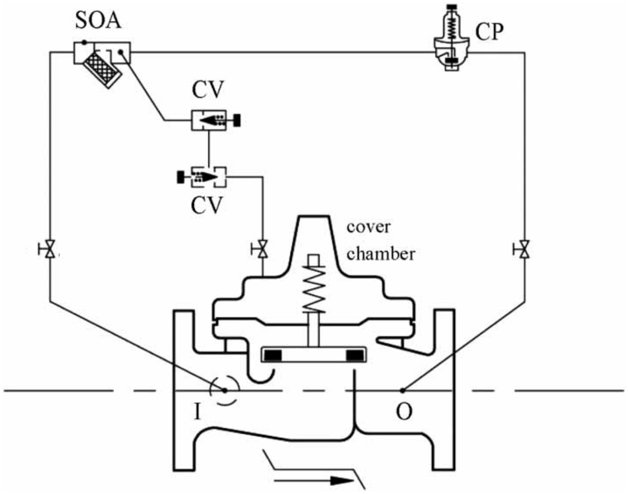

Figure 3 | Schematic of the PRV (modified from http://www.cla-val.com/waterworks-pressure-reducing-valves): I = inlet section, O = outlet section, CV = check valve, SOA = strainer-orifice assembly, CP = control pilot.

During the tests, H_{NSP} is fixed at 5, 10 and 26 m. Pressure signals, H, are acquired by piezoresistive transducers with a frequency acquisition of 1,000 Hz at: section V, placed immediately upstream of MV, 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, and at the supply tank (Figure 1). 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 PRV relative opening degree, δ, is measured by means of an electronic valve position indicator.

PRV HYDRAULIC CHARACTERIZATION (STEADY-STATE TESTS)

Steady-state tests have been carried out to characterize the PRV: the minor head loss, ζ, has been measured for different values of δ ($\delta = 0\%$ means fully closed valve, whereas 100% means fully open valve), and Q. Experiments have concerned turbulent flow – the usual flow regime in WDNs – and for each relative opening degree, the minor head loss

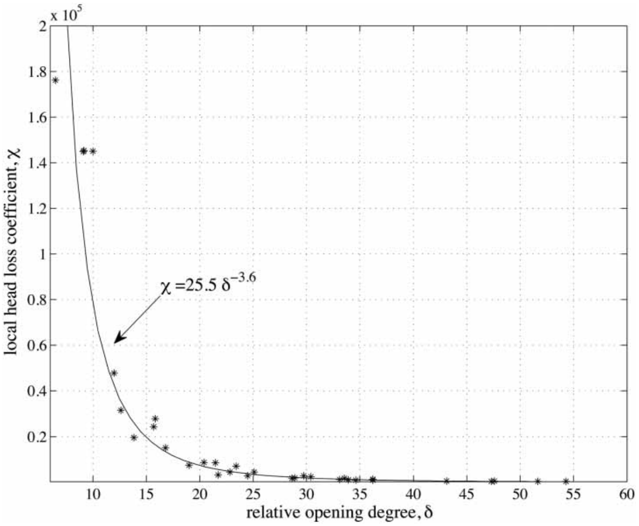

Figure 4 | PRV steady-state characterization: experimental values of χ vs. δ and the interpolating curve.

coefficient, χ, has been determined through the following equation (Idel'cik 1986):

$$\zeta = \chi \frac{Q^2}{2gA^2} \tag{1}$$

where g = gravity acceleration and A = pipe area. In Figure 4, the values of χ vs. δ, exhibit a typical power law behaviour (Idel'cik 1986), with the coefficient of determination, R^2, equal to 0.985. The main differences between the interpolated curve and the experimental data happen at the small relative openings because of the unavoidable errors occurring for small values of Q, according to the findings of Brunone & Morelli (1999).

Since the PRV is not a partially closed in-line valve with a fixed opening degree (Meniconi *et al.* 2011a, 2011b), but a self-adjusting opening valve, H_{NSP} and the inlet pressure, H_U, play a crucial role.

To better understand the experimental behaviour of the PRV for a given Q but different H_U and H_{NSP}, the hydraulic grade line for the tests of Table 1 is reported in Figure 5. Figure 5(a) shows two tests with the same Q (=2.64 l/s) and inlet condition ($H_U = 46.0$ m) but a different nominal set-point, which constrains the PRV to be more closed for test no. 1 ($\delta_1 = 23.2\%$ and $\chi_1 = 4{,}425$) with respect to test no. 2 ($\delta_2 = 26.6\%$ and $\chi_2 = 2{,}786$). Figure 5(b) concerns two tests with the same Q (=1.90 l/s) and nominal set-point but a different inlet condition ($H_U = 21.6$ m for test no. 3 and $H_U = 48.4$ m for test no. 4). In essence, the PRV has been automatically settled to a larger opening degree for test no. 3 ($\delta_3 = 25.6\%$ and $\chi_3 = 3{,}156$) with respect to test no. 4 ($\delta_4 = 19.0\%$, and $\chi_4 = 8{,}726$).

Table 1 | Steady-state tests for evaluating the role of the inlet and outlet pressures

Test (no.)	Q (l/s)	H_U (m)	H_{NSP} (m)	χ (–)	δ (%)
1	2.64	46	10	4,425	23.2
2	2.64	46	26	2,786	26.6
3	1.90	21.6	10	3,156	25.6
4	1.90	48.4	10	8,726	19.0

In order to make the experimental results more general and clear, the following dimensionless quantities are considered: $h = H/H_{NSP}$, $Re = VD/\nu$, $\theta = t/\Theta$, where Re is the Reynolds number (V = mean flow velocity and ν = fluid kinematic viscosity), and Θ is the pipe characteristics time (=$2L/a$), with the pressure wave speed, a, assumed as equal to 368 m/s, according to Pezzinga *et al.* (2016).

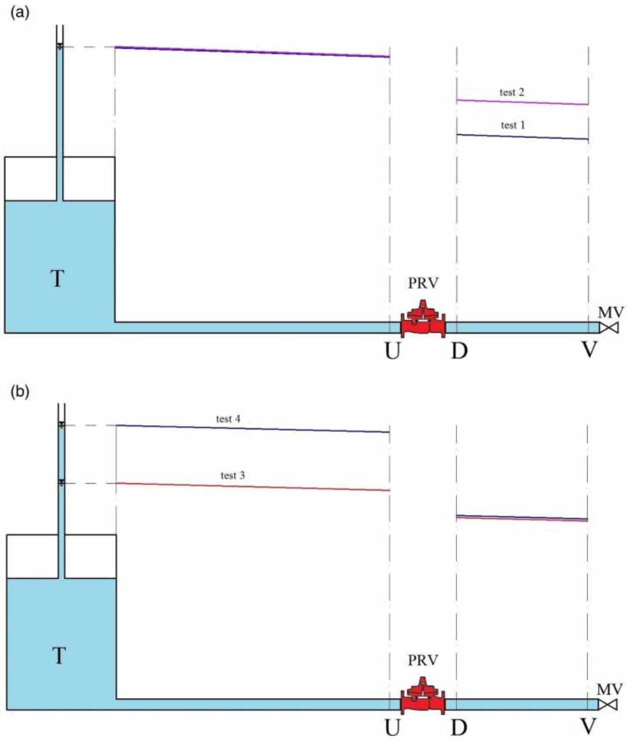

Figure 5 | Steady-state hydraulic grade line, with the sketch of the experimental setup for: (a) tests no. 1 and no. 2; (b) tests no. 3 and no. 4 of Table 1.

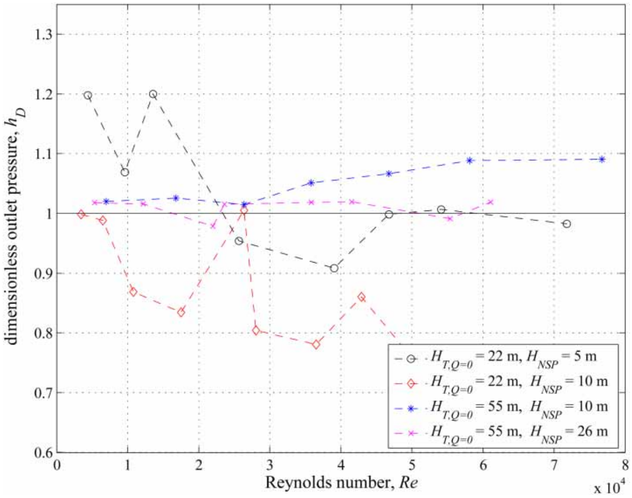

Figure 6 | Dimensionless PRV outlet pressure, h_D, vs. the Reynolds number, *Re*.

Further steady-state tests have been executed to check the PRV behaviour for different values of *Re*. Figure 6 plots show that the difference occurring between the nominal set-point and the measured value of downstream pressure does not depend on *Re*.

PRV TRANSIENT RESPONSE (UNSTEADY-STATE TESTS)

This section shows the results of the tests (Table 2) executed to check the performance of the PRV during transients simulating changes specified by the user. In the laboratory tests, the discharge is changed by (i) manoeuvring the MV valve and (ii) varying the functioning conditions of the pumps feeding the tank. To cover the broadest range of the possible events taking place in WDNs, both short (i.e., with a duration of few seconds), and long (i.e., with a duration of some hours) tests have been considered. Moreover, to check the effect of the characteristics of the experimental setup, two different lengths of the pipe downstream of the PRV, L_2, have been analysed. For the sake of clarity, transient tests are examined separately below on the basis of their duration; in Table 2 Re_i (Re_f) indicates the steady-state Reynolds number before (after) the manoeuvre.

Short duration transients

The effect of the complete closure of the manoeuvre valve (MV) placed at the pipe end section can clearly be inferred by signals reported in Figure 7: for a given Re_i, the plots in the left (Figure 7(a)–7(c)) and right (Figure 7(d)–7(f)) part of the graph refer to a fast and slow closure of MV, respectively. With regard to the fast closure manoeuvre (Figure 7(a)–7(c)), it can be observed that the fast increase of h_D causes the simultaneous increase of h_U, which oscillates because of the effect of the upstream boundary condition at the tank (Figure 7(a)). After the first phase of the transient, i.e., when the oscillations end, the value of h_D (larger than 1) coincides with the one of h_U since the PRV does not close fully. The same behaviour happens for the slow closure manoeuvre (Figure 7(d)–7(f)): the much smoother trend of the signals – with the pressure oscillations suppressed both upstream and downstream of the PRV – is clearly due to its larger duration.

Table 2 | Unsteady-state tests for evaluating the PRV transient response (H_{NSP} = 26 m)

Type of transient	Test (no.)	Type of manoeuvre	Main characteristics
Short duration	5	MV complete fast closure	$Re_i = 3.43{*}10^4$, $L_2 = 69.7$ m
	6	MV complete slow closure	
	7	MV complete fast opening	$Re_f = 3.29{*}10^4$, $L_2 = 69.7$ m
	8	MV complete slow opening	
	9	Pump trip	$Re_i = 3.43{*}10^4$, $L_2 = 69.7$ m
	10		$Re_i = 2.47{*}10^4$, $L_2 = 69.7$ m
	11	Pump start up	$Re_f = 3.43{*}10^4$, $L_2 = 69.7$ m
	12		$Re_f = 2.47{*}10^4$, $L_2 = 69.7$ m
Long duration	13	Daily demand pattern	$L_2 = 69.7$ m
	14		$L_2 = 181.8$ m

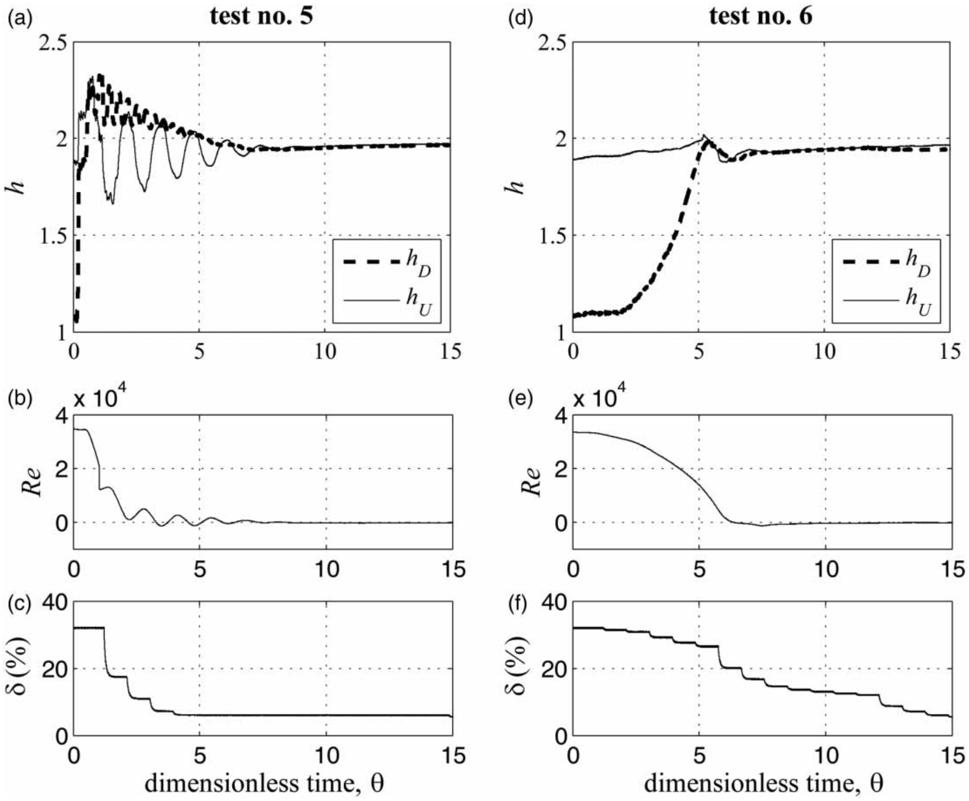

Figure 7 | Short duration transients due to the fast (test no. 5) and slow (test no. 6) complete closure of MV.

To check the performance of the PRV during transient causing an increase of *Re*, opening manoeuvres of MV with a different duration have been carried out (Figure 8). The fast opening manoeuvre (Figure 8(a)) generates a sudden decrease of h_D, quite remarkable oscillations of h_U (20% of H_{NSP} at most), and an increase of *Re* (Figure 8(b)) and δ (Figure 8(c)). As for the closure manoeuvre, the effect of a longer duration of the opening manoeuvre is a much smoother behaviour of all signals: particularly, in Figure 8(d), h_U exhibits much smaller oscillations (3% of H_{NSP} at most). It is worth noting that for both transients of Figure 8 the final value of h_D coincides approximately with 1 (Figure 8(a) and 8(d)).

To simulate an increase in user demand, the pressure upstream of the PRV has been reduced by abruptly stopping the electricity supply of the pump. Transients due to the pump trip are reported in Figure 9, where the plots in the left (Figure 9(a)–9(c)) and right (Figure 9(d)–9(f)) part of the graph differ for the value of Re_i. These signals exhibit clearly that h_U decreases quite fast, whereas in the first phase of the transient, h_D (Figure 9(a) and 9(d)) and *Re* (Figure 9(b) and 9(e)) are almost constant since the PRV opens (Figure 9(c) and 9(f)), and the local head loss through it decreases. Thus, it can be stated that in such a phase the opening of the PRV offsets the decrease of h_U. For h_D smaller than 1 the action of the PRV is no longer necessary for pressure management (i.e., the small value of *Re* makes the PRV unreliable). Such a behaviour is more evident for the smaller value of Re_i: in fact, at the end of test no. 9, δ is almost constant, whereas for test no. 10 there is not a clear automatic control of the opening degree and δ decreases (Figure 9(f)).

A quite different behaviour can be observed for the transients due to the pump start up (Figure 10), which simulates a decrease of the users' demand in WDNs. In comparison to the pump trip, for both values of Re_f, there is a much closer link between h_U and h_D (Figure 10(a) and 10(d)) as well as a larger rate of change of *Re* (Figure 10(b) and 10(e)). The reason why in the first phase of the transient h_D increases accordingly with h_U is that, in that period of time, h_D is

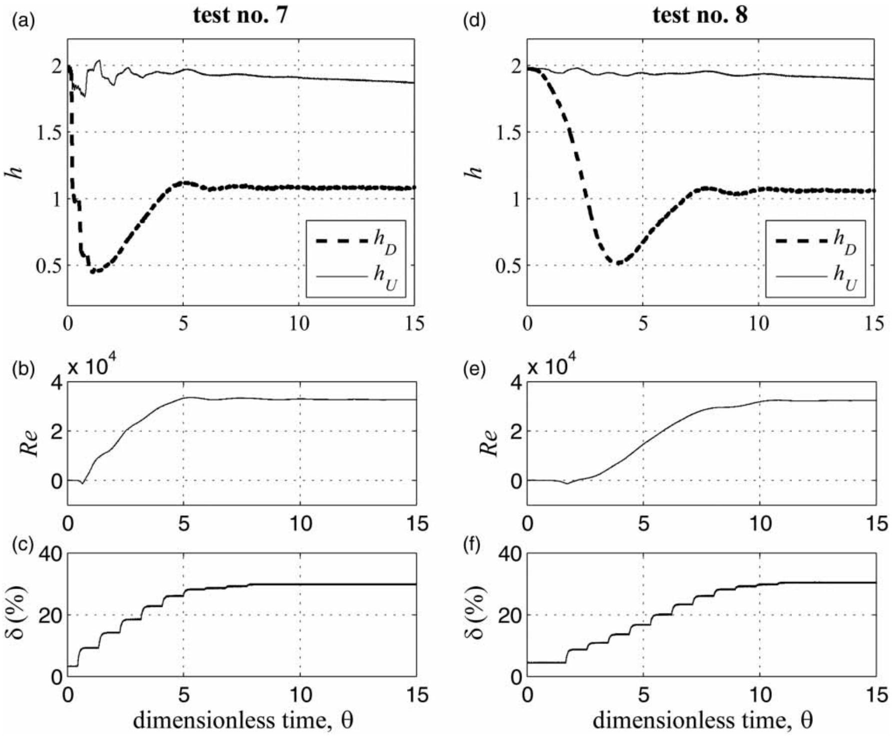

Figure 8 | Short duration transients due to the fast (test no. 7) and slow (test no. 8) complete opening of MV.

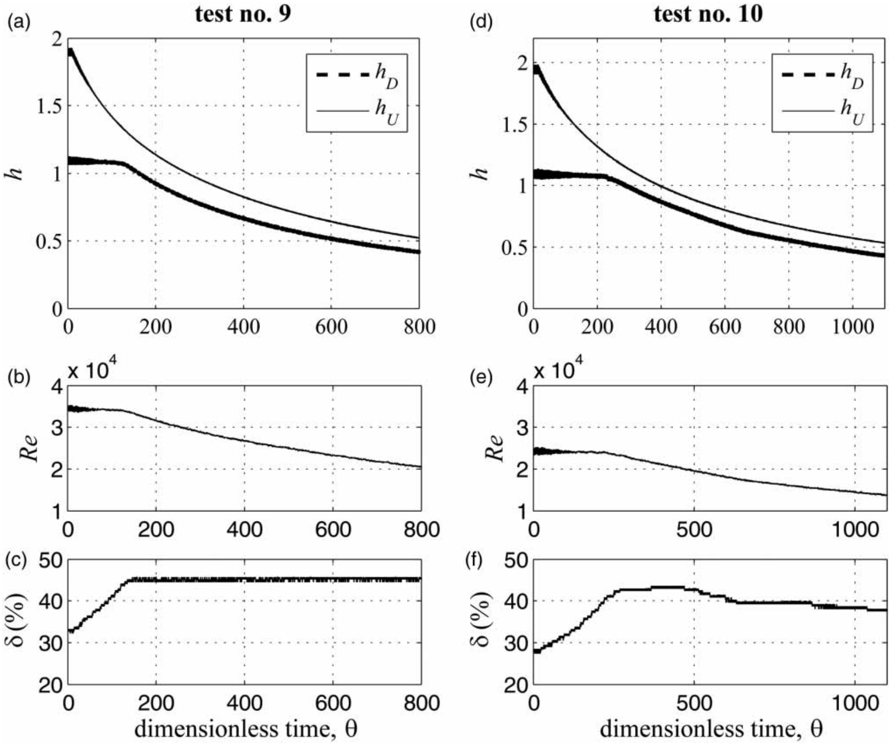

Figure 9 | Short duration transients due to the supply pump trip.

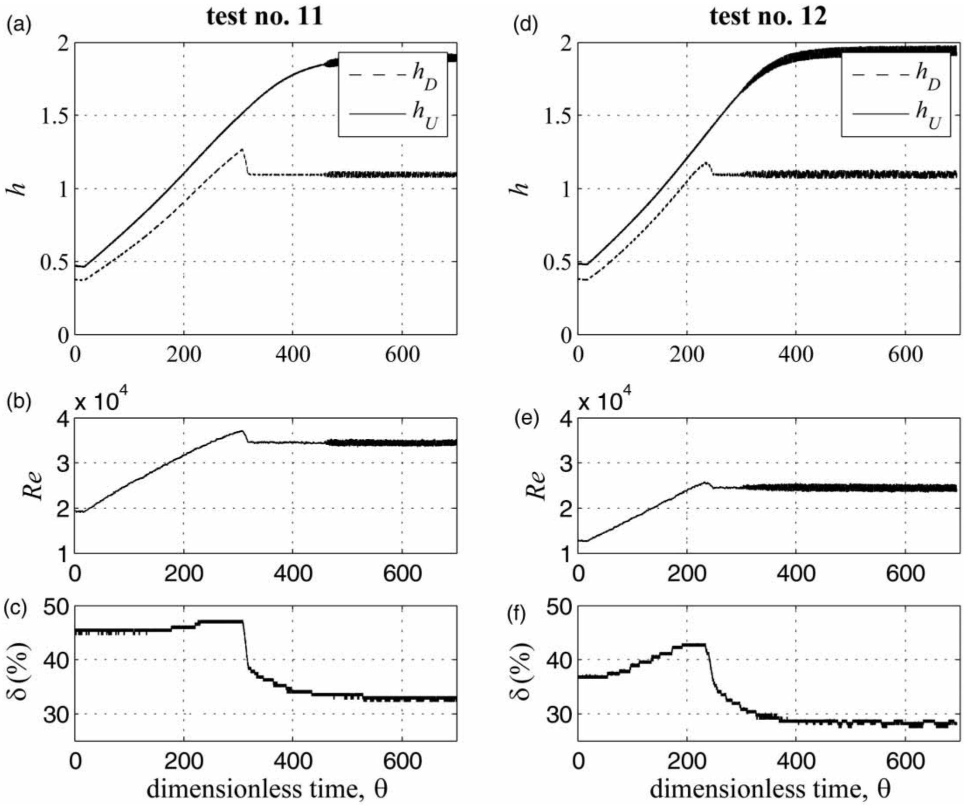

Figure 10 | Short duration transients due to supply pump start up.

smaller than 1. On the contrary, for both tests an abrupt reduction of the PRV opening degree (Figure 10(c) and 10(f)) and *Re* (Figure 10(b) and 10(e)) happens at about $t = 340$ s for test no. 11, and $t = 260$ s for test no. 12, when h_D becomes larger than 1 (Figure 10(a) and 10(d)).

Long duration transients

Long duration (i.e., 12 hours) tests no. 13 and 14 of Table 2 have been executed to check the PRV performance when a typical demand pattern of WDNs with specified changes at designated times happens. In test no. 13, two peaks of the demands are imposed by regulating MV: about at the 4th ($\theta = 1.33$) and 9th hour ($\theta = 3.13$), respectively (Figure 11(b)). As expected, the PRV opening (Figure 11(c)) is directly proportional to the variation of *Re* (Figure 11(b)). In the time period far away from the demand variations, while h_U changes accordingly with the pump characteristic curve – it diminishes with increasing *Re* – h_D is about constant around 1 (Figure 11(a)). As pointed out in the previous section, the manoeuvre of MV modifies the pressure values with a maximum oscillation equal to 13% for h_U, and 38% for h_D.

To look at these variations in more detail, Figure 12 reports two magnified visions of Figure 11 in the time interval when the largest demand decrease (Figure 12(a)–12(c)) and increase (Figure 12(d)–12(f)) take place. In both cases, the larger pressure variations happen downstream of the PRV, whereas smaller pressure changes occur upstream, because of the combined actions of the supply tank and the PRV that almost isolates the upstream branch of the pipe.

The effect of the characteristics of the experimental setup has been checked in test no. 14. Particularly, the same demand pattern of test no. 13 (Figure 11) has been used but in a quite different system. In fact, the length, L_2, of the pipe downstream of the PRV has been significantly increased (181.1 m compared to 69.7 m). Figure 13

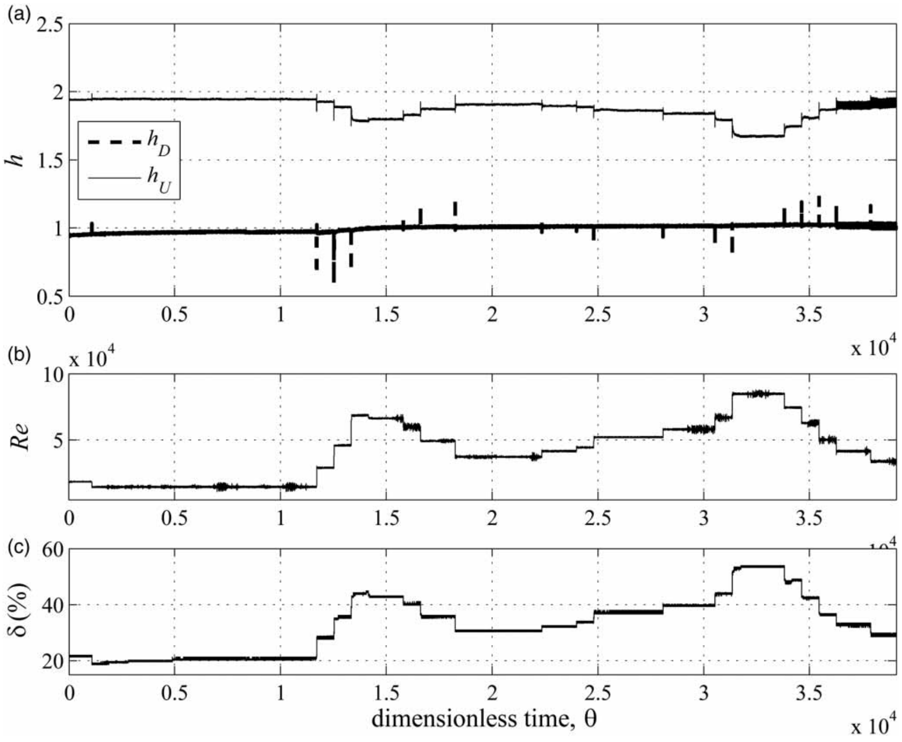

Figure 11 | Long duration transient due to the flow variation modulated by MV (test no. 13, with $L_2 = 69.7$ m).

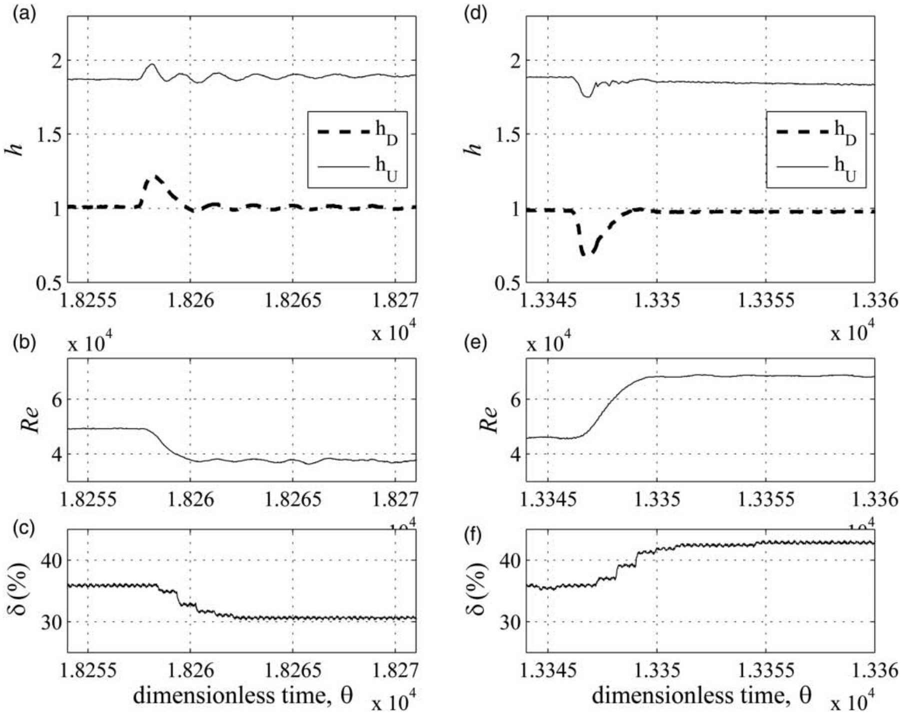

Figure 12 | Long duration transient (test no. 13): magnified vision of Figure 11 in the time interval when the largest demand decrease (a)–(c) and increase (d)–(f) take place, respectively.

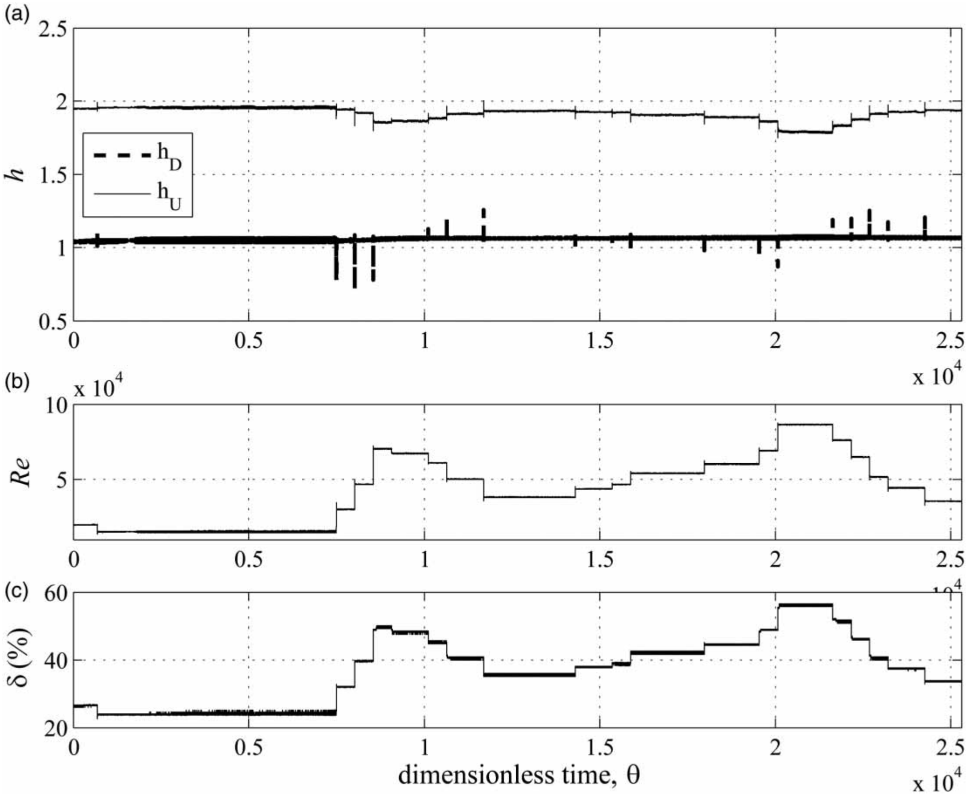

Figure 13 | Long duration transient due to the flow variation modulated by MV (test no. 14, with $L_2 = 181.8$ m).

demonstrates that the value of L_2 does not affect significantly the PRV transient response since all the signals do not change appreciably.

PRV RESPONSE TO A LONG DURATION UNSTRESSED CONDITION

A continuous series of transients typifies what the actual functioning conditions of a WDN are: in fact, the variability of the users' demand signifies a repeated series of discharge variations, which give rise to as many pressure changes. The entity of such pressure variations depends on not only the value of the discharge change but also the topology of the system and in which part it happens. Moreover, the characteristics of the boundary conditions play a crucial role. As an example, a given incoming pressure wave splits into a number of smaller pressure waves at a cross-junction whereas it doubles at a dead end. As a consequence, in a WDN the pressure regime is the result of the overlapping of pressure waves coming from different parts of the system (e.g., Meniconi *et al.* 2015b) and the flow regime can be assimilated to a sort of 'permanent' unsteady condition. This implies that during the day – as for the above long duration transients – each part of the system is continuously more or less stressed.

Transients discussed in the previous section are examples of possible pressure surges where the PRV plays an important role but with its behaviour – i.e., its response – being a clear consequence of the WDN functioning conditions (as an example: if h_U increases, the PRV closes and vice versa). On the contrary, in this section a 'limit' flow condition is examined to point out the PRV response to a long duration unstressed condition according to the intrinsic characteristics of the system (i.e., pipe material). The starting point of test no. 15 is the transient caused by the complete closure of the manoeuvre valve with $Re_i = 2.88{*}10^4$ – i.e., a transient very close to the one in Figure 7 – with some pressure oscillations propagating upstream of the PRV (Figure 14(a)) and, as a final condition,

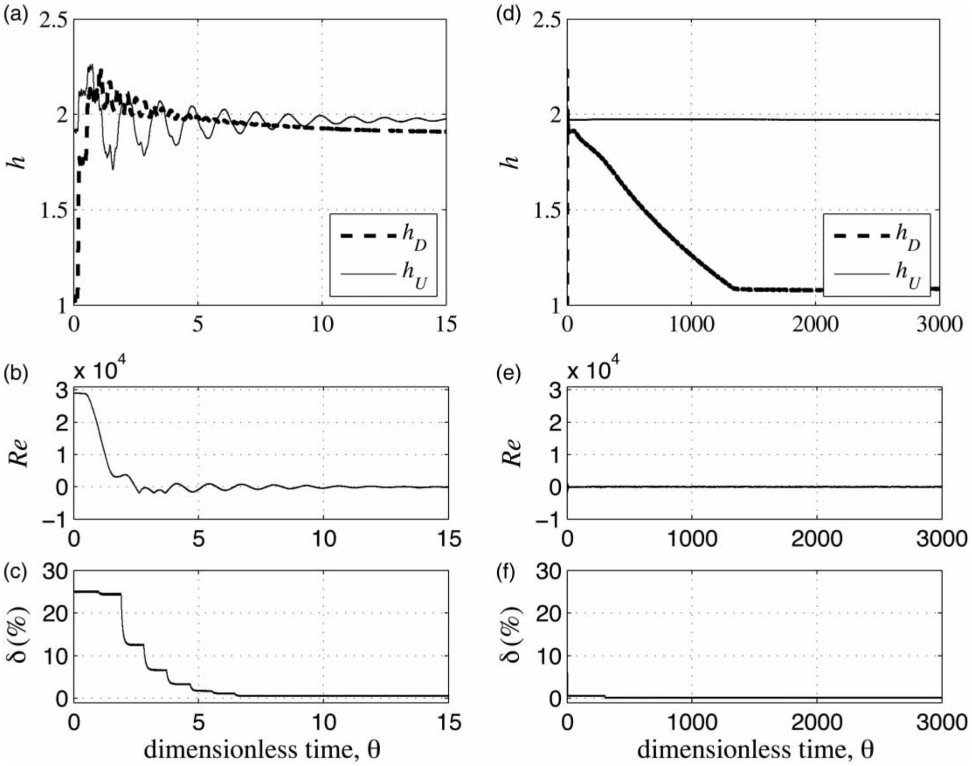

Figure 14 | Transient due to the fast complete closure of MV: (a)–(c) short term monitoring, (d)–(f) long duration unstressed condition monitoring.

$Re_f = 0$ and $h_U \cong h_D$. In fact, the PRV is not fully closed (Figure 14(c)), but its opening degree is quite close to zero. In other words, the system becomes a unique system and, since the PRV is inactive but partially open, static conditions take place. As time passes, it can be observed that h_D moves towards 1, whereas h_U does not change (Figure 14(d)) even if the measured *Re* is equal to zero (Figure 14(e)). Such an apparently unaccountable behaviour is justified, having in mind that a PRV only works if there is a flow through it or, in other words, it cannot reduce h_D in a static system. This implies that a very small discharge takes place – undetectable by the installed magnetic flow meter – due to the elasticity of the pipe (a quite deformable polymeric one) system. In the meanwhile, since the value of the opening degree δ is close but not exactly equal to zero, when the effects of the initial closure manoeuvre vanish (Figure 14(f)), the PRV closes progressively until the flow stops completely. At this point the system is static, but with h_D equal to 1, because the upstream and downstream sides of the pipe are not actually connected anymore. Ultimately, in such a behaviour of the PRV, which is due to a sort of ideal unstressed condition, the nominal set-point is slowly fulfilled and the PRV fully closes. The mechanism that generates a small flow, making the PRV active, depends on the characteristics of the pipe system: in the examined case, it is due to the remarkable deformation of the pipe and the steady pumping supply.

CONCLUSIONS

The target of the PRVs is to set the pressure downstream of a selected node at a given value (i.e., the nominal set-point) regardless of the upstream one. As a consequence, they play a crucial role in pipe system management since they allow reduction of leakage through pressure control.

Despite their great importance, in the literature there is a lack of knowledge about their actual performance. In this paper, laboratory tests have been executed on a standard PRV to characterize the steady-state behaviour and to examine the transient response.

Steady-state tests concerned the evaluation of the local head loss for different relative opening degrees in a turbulent regime. 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 behaviour of both the inlet pressure and nominal set-point has been examined.

The aim of the unsteady-state tests is to check the response of the PRV to transients generated to simulate the variability of users' demand and supply conditions in WDNs. To explore a broad range of functioning conditions, different types of transients have been examined: (i) short duration events caused by discharge changes due to closing and opening manoeuvres of a controlled motorized valve or supply pump trip and start up; and (ii) long duration tests during which a typical daily demand pattern has been considered. Moreover, a long duration unstressed condition test has been monitored.

The executed tests demonstrate the versatility of PRVs as a powerful tool for pressure management in WDNs. Their transient response is appropriate with small pressure oscillations generated by the PRV self-adjustment. Proper PRV modelling must include both its mechanical behaviour and the characteristics of the pressure pipe system in which it is installed.

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