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Laboratory experiments and simulation analysis to evaluate the application potential of pressure remote RTC in water distribution networks

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A B S T R A C T

Experimental tests were performed to demonstrate applicability of remote real time control (RTC) of pressures for leakage reduction in water distribution networks (WDNs). The experimental tests were carried out in a laboratory pilot system equipped with a motorized plunger valve. A RTC system with the adoption of an integral-type control algorithm was implemented in order to adjust the valve on the basis of pressure measurements acquired in real time. A numerical model of the pilot system was used to verify the suitability of the hypothesis of steady-state conditions in simulating the laboratory tests. The results of the experiments show that, under appropriate calibration of the control algorithm, the RTC system is able to perform effective control of the pressure. Comparison between results of the simulations and experiments reveals that the steady-state model describes correctly the evolution of the pressure control processes observed in the laboratory pilot system, thus opening perspectives for testing remote RTC schemes for leakage management in real WDNs.

1. Introduction

Active control of pressure is considered as one of the most promising methodologies to reduce water leakages in water distribution networks (WDNs) (Araujo et al., 2006; Creaco and Walski, 2017). Evidence has amply proven that the increase in background losses (such as the leakage from pipe breaks, joints, etc.) is markedly correlated to the increase in operational pressure in the pipes of the distribution network (Thornton, 2002; Ciaponi et al., 2015).

Traditional pressure reduction methods generally make use of pressure control valves (PCVs). Normal practice is to install such devices at the inlets to the districts of the WDN and to set them properly in order to lower the piezometric level of the whole district (Thornton, 2002). Typically, PCVs are used for local control, with the objective of achieve and maintain the desired pressure set-point (locally) at the site of installation, immediately at the outlet of the valve. Pressure set-point can be constant or vary during the day according to prefixed time-scheduling. Most common types of PCVs include mechanically/hydraulically driven devices that need to be calibrated in situ (usually, by adjustment of a secondary screw-based pilot valve) as a function of pressure (Prescott and Ulanicki, 2008; Nicolini and Zovatto, 2009; AbdelMeguid et al., 2011). Alternatively, the valve can be adjusted on the basis of pressure measurements using electronic controllers (Janus and Ulanicki, 2018).

In principle, controlling PCVs according to local values of pressure does not assure proper control of the piezometric levels of the downstream WDN; in fact, such a type of control is significantly affected by the uncertainty in the estimation of the spatio-temporal distribution of nodal water demands, leakages, as well as energy losses in the WDN.

Recently, focusing on leakage reduction, various researchers (Campisano et al., 2016; Berardi et al., 2017; Page et al., 2017a) have explored the potential of methodologies based on the use of remote real time control (RTC) for improving pressure regulation in WDNs. Depending on the network characteristics, RTC systems can suitably replace traditional pressure control strategies by moving from local to remote control technologies (Creaco and Walski, 2018); indeed, remote RTC systems use (distributed) remote information about the current status of the WDN in order to improve the effectiveness of pressure (and thus leakage) control strategies. Typically, one or more pressure sensors are installed in the

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network, in nodes that are far (remote) from the valve site. Normally, such nodes are placed in the downstream part of the district, selected among those with low pressure (Campisano et al., 2010). Information obtained by the continuous acquisition of remote pressure measurements is transmitted through a specific communication infrastructure in real time (normally using GSM or dedicated radio lines), being finally used to adjust dynamically the upstream control valves (Campisano et al., 2010; Giustolisi et al., 2017). RTC is implemented by means of controllers, devices that, based on information received by the sensors in the network, calculate and provide commands to valve actuators in order to adjust the flow process and drive control node pressure to the set-point.

Much of the available studies on RTC (e.g., Campisano et al., 2010; Giustolisi et al., 2017; Page et al., 2017b; Creaco et al., 2018) have mainly invoked use of simulation approaches to demonstrate advantages of remote control as compared to local control. Some approaches (Janus and Ulanicki, 2018; Galuppini et al., 2019) consider use of sophisticated methods proper of control engineering with a focus on system design in order to control pressure signals in WDNs including high-frequency components. Such type of approach aims at accurate control of pressure signals determined by pulsed demands in the WDN. However, tracking such signals requires control frequency that may be incompatible with the valve operation, or increase malfunctioning/failure of the valve itself. Conversely, other approaches focus on the hydraulic objective of reducing water leakages in the WDN. To achieve this objective, the control of the (low-frequency) pressure component associated to the daily pattern of the water demands in the network has been recognized as sufficiently accurate (Campisano et al., 2016; Creaco et al., 2019).

In such a context, simulations have been carried out to test performances of various control algorithms, that include hydraulics-based algorithms (AbdelMeguid et al., 2011; Giustolisi et al., 2017) and algorithms based on the use of PID (Proportional-Integral-Derivative) logic. A complete review of available algorithms for remote RTC of pressure in WDNs can be found in the recent work by Creaco et al. (2019).

PID is probably the most widespread type of control logic in embedded programmable logic controllers (PLCs), owing to its conceptual simplicity, and the opportunity for the continuous adaptation to the controlled system (Åström and Hägglund, 1984). This type of control has been used in various modalities in the field of water engineering for the control of both urban drainage systems (Campisano et al., 2000; Schuetze et al., 2004; Pothof and Kooij, 2007) and water distribution systems. Results from the literature show that effective valve control in WDNs can be obtained by adopting algorithms which do not necessary include all the three terms of the complete standard PID. In any case, accurate calibration of the used algorithm is required (Campisano et al., 2012; Ziegler and Nichols, 1942). Creaco and Franchini (2013), Creaco (2017), Page and Creaco (2019) report improvements in the control action with algorithms that include use of simultaneous measurements of pressure and flow discharge (although at higher costs and complexity of implementation).

Although the potential for application of remote RTC in WDNs was explored by various studies, much of these studies were carried out using numerical approaches. Conversely, up to now, only few investigations have concerned the development of experiments to evaluate the RTC potential at the laboratory and/or field scales. An example of laboratory application is provided by Fontana et al. (2018a) which developed an integral (I) control algorithm to adjust settings of a pilot valve-operated PCV. The same authors tested with success the developed algorithm in a district of the WDN of the city of Benevento, Italy (Fontana et al., 2018b), confirming suitable pressure control and water leakage reduction in the network. However, the control system adopted by the authors was not fully implemented as a scheme of remote RTC; in fact, such control system adjusts the outlet pressure of the valve by using an empirical model of the network to estimate head losses between the site of the PCV and the remote control node. A very similar approach was used by Bakker et al. (2014) for the dynamic control of flows and pressures in Poznań, Poland through performing real time adjustment of pumps settings. Also in this case, a pressure-demand model of the network was calibrated offline and used for determining the settings of the pumps. Therefore, the approaches adopted in previous papers are not based on the use of pressure measurements transmitted in real time from the network to the control site. With regard to the used control, such approaches make use of a closed-loop scheme for controlling local pressure at the valve site while relying on the use of an open-loop for the control of pressure at the remote node. In principle, if the relationship between local and remote pressure is not modeled properly, even a good regulation of local pressure might not assure effective control at the remote node. In these cases, large network portions may exhibit pressure excess/deficit during the day as compared to set-point values.

The objective of this paper is twofold. Novel experiments were carried out in a pilot rig at the laboratory scale to verify applicability and effectiveness of remote RTC for pressure control with reference to leakage reduction in WDNs. Remote RTC was implemented by adjusting in real time the opening degree of a motorized plunger valve. Differently from previous literature studies, the valve control is based exclusively on pressure measurements acquired in remote (and transmitted) in real time using a closed-loop control scheme. As further objective, the paper aims at demonstrating the suitability of the hypothesis of steady-state conditions to simulate the RTC laboratory experiments. To achieve this objective, an already available numerical hydraulic model of the pilot system was upgraded with a control module and used for both the preliminary tuning of the controller and the successive simulations.

The paper is structured in sections. First, the experimental methods are presented, including the description of the laboratory pilot system, the implemented RTC system architecture, the framework of the experiments, as well as the used numerical model. Secondly, results of the different experiments are presented with specific emphasis on the pressure control performance of the RTC system. Third, simulation results are discussed and compared with results of the experiments to demonstrate the suitability of the steady-state hypothesis for the simulation of real time pressure control for leakage reduction. Finally, the discussion concerning the analysis of the results is reported including potential and limitations of the used approach, followed by main conclusions of the research and future perspectives.

2. Materials and methods

2.1. Description of the laboratory pilot system

The pilot system was installed at the Laboratory of Hydraulics of the Department of Civil Engineering and Architecture of the University of Catania, Italy. The system mainly consists of 4 subsystems: *i)* an upstream head tank equipped with a pump (outside the laboratory room); *ii)* the adduction pipe section from the pump to the laboratory room; *iii)* the pipe section of interest for the experiments; and *iv)* the recirculation system to convey back flow to the upstream tank. The upstream tank has a maximum storage capacity of about 70 m^3 and is supplied by the University Campus water distribution system. The pump allows maximum head of about 85 m and maximum flow discharge close to 25 L/s.

The adduction pipe is a 33 m long iron pipe with nominal diameter DN100, and conveys the pumped flow to the section of interest for the experiments. The pipe shows significant internal corrosion, typical of water distribution network pipes in operation by several years (estimated Strickler roughness coefficient close to 70 $m^{1/3}/s$).

The section of interest for the experiments has the same geometrical and hydraulic characteristics of the adduction pipe. The section (see the sketch of Fig. 1) is made of a vertical ascending segment equipped with a gate valve operated manually; an intermediate sub-horizontal segment (3% slope) equipped with the instrumentation for pressure control; and a final vertical descending segment, equipped with another manual gate valve, that conveys the flow to the recirculation system. All monitoring and control equipment is installed in the intermediate segment. In detail, going from upstream to downstream, the segment hosts a valve for air purge; an upstream sensor of pressure (later in the text indicated as US); an electromagnetic flowmeter (DN80); the motorized plunger valve used for controlling the pressure; a ball valve (DN100); a downstream pressure sensor mounted in the section that was identified as the remote control node (CN); an additional air purge valve.

Pressure sensors are piezo-resistive probes, with a range of measurement 0–10 bar, full scale error ±0.003, resolution 0.1% of full scale, and analogic output 4–20 mA. The electromagnetic flowmeter allows measurement of the flow discharge in the range 0.8–80 L/s with errors in the order of 1% and 0.5% for flow velocities between 0.1 and 0.5 m/s, and 0.5–10.0 m/s, respectively.

The plunger valve is DN80 mm in size. Although this type of valve requires higher electric power than other mechanical PCVs, field experience shows that it allows accurate flow and pressure control in WDNs. Two short conic (converging and diverging) trunks were used as joints between the plunger valve and the pipe DN100. Fig. 2 shows the curve of the valve resistivity $\xi_{plunger}$ [−] as a function of the opening degree of the valve shutter a [%]. The valve provides a value of $\xi_{plunger} = 3.1$, when the valve is fully open.

An electric actuator equipped with both reduction group and multi-turn device is coupled to the plunger valve. The actuator enables the possibility to adjust the opening/closure degree of the valve shutter by receiving signals from an external control unit (for example signals sent by a remote PLC). Specific electronic devices mounted on board also allow analogic transmission of torque values and position of the valve shutter at any instant of the control action. The ball valve (DN100) was used in the experiments to emulate energy losses determined by the network when the remote control node is far from the control valve site. Since the energy loss as induced by the ball valve varies with the conveyed flow, the valve may locally replicate the impact of the distributed energy loss in WDNs, thus allowing emulating properly losses due to the variability of water demands. Finally, the gate valves (DN100) placed in the two vertical segments were used to setup the initial condition of the pilot system (to determine appropriate flow discharge and pressure values in the system) for the different experimental tests developed.

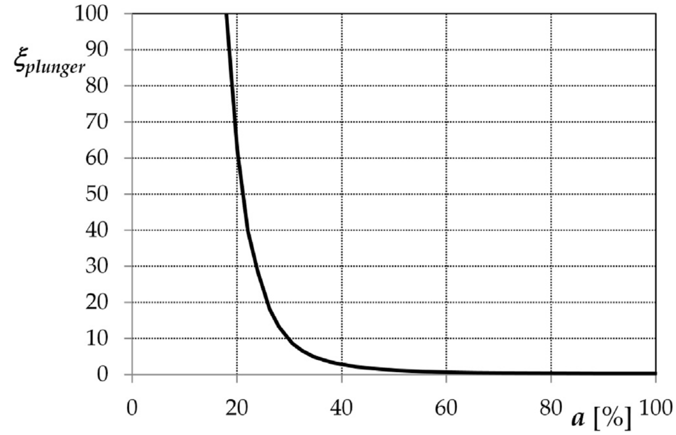


Fig. 2. Resistivity curve of the installed plunger valve as a function of the valve opening degree.

2.2. Control system structure and algorithm

The control system was structured adopting a closed-loop scheme of remote RTC to control pressures in the laboratory pilot. The system includes use of a PLC that collects all the measurements acquired by the pressure sensors and by the flowmeter. The PLC allows also addressing control commands to the actuator of the plunger valve by means of analog signals in the range 0–20 mA. A digital clock supports real time operation of the control system enabling run times smaller than 0.7 ms. A personal computer connected to the PLC monitors the control process in real time and stores the acquired measurements (i.e., the recorded values of pressure, flow discharge, and opening degree of the valve shutter). LabVIEW software (Travis and Kring, 2006) was used as it allows easy implementation of algorithms for the valve control using input signals from the PLC. From a practical viewpoint, the objective of the control algorithm is to adjust (step-by-step) the setting of the valve shutter (i.e., determine the needed energy dissipation at the valve site) in order to drive the pressure at the remote CN to the set-point. Therefore, the pressure value p_t [bar] at time t provided by the sensor at the control node was used for the algorithm application. Notably, at each time step Δt_c of the control action, the adopted algorithm adjusts the valve (provides the displacement Δa [%] of the valve shutter), based on the deviation $e_t = p_t - p_{sp}$ [bar] at time t between p_t and the set-point pressure p_{sp} [bar] as:

$$\Delta a = a_{t+\Delta t_c} - a_t = -K \cdot e_t \tag{1}$$

where a_t [%] and $a_{t+\Delta t_c}$ [%] are the valve shutter opening degrees at times t and $t + \Delta t_c$, being $a = 100\%$ when the valve is fully open. Previous equation shows the shutter displacement Δa to be proportional to e_t by means of the gain parameter K [percent/bar]. Therefore, in principle, with respect to the shutter position a, Eq. (1) shows the characteristics of an integral-type control algorithm.

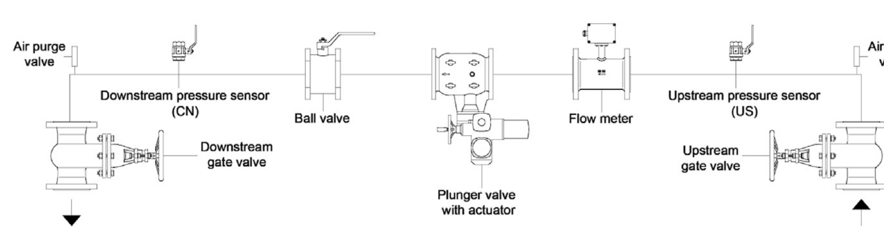


Fig. 1. Sketch of the laboratory pilot system. Section of interest for the experiments with monitoring and control equipment.

Moreover, the negative sign in Eq. (1) allows considering the negative relationship between Δa and e_t, if gain K is assumed intrinsically positive.

In principle, the integral action would ensure achievement of the set-point if no derivative action is present and in presence of step reference signals and step process disturbances (Galuppini et al., 2019). The gain K plays an important role on the dynamics of the control system and must be calibrated to assure effective control actions. Calibration might result in a very complex operation for WDNs because of the significant non-linearity in the response of the network to flow variations (nodal demand changes in time and space).

Another parameter having significant impact on the performance of the RTC system is the control time step Δt_c. Selection of the value of this parameter strictly depends on the control objective and should be consistent with the characteristic time of the process and with the used K value (Galuppini et al., 2020). In particular, for the control of water leakage in WDNs, the choice of Δt_c can be conveniently related to the low-frequency component of the pressure signal (typically varying accordingly to the hourly demand pattern in the network). The new value $a_{t+\Delta t_c}$ as evaluated by Eq. (1) is prescribed to the valve in case that $a_{min} \leq a_{t+\Delta t_c} \leq a_{max}$, being a_{min} [%] and a_{max} [%] the smallest and the largest values allowed for the valve opening degree, respectively. While a_{min} is normally suggested by the manufacturer in order to avoid cavitation, a_{max} is generally equal to 100%. Since the adoption of a_{min} and a_{max} determines the saturation of the control action, an anti-windup approach was implemented to avoid pressure overshoots/undershoots. This was obtained by prescribing $a_{t+\Delta t_c} = a_{min}$ to the valve if Eq. (1) provides $a_{t+\Delta t_c} < a_{min}$, and $a_{t+\Delta t_c} = a_{max}$ in the case that $a_{t+\Delta t_c} > a_{max}$.

2.3. Framework of the experiments

Setting of the RTC system required devoting attention to several aspects that are relevant to the control performance. Firstly, the motorized plunger valve was set in order to assure a relatively low value of the opening/closing velocity of the shutter (2.2% of the total run per second), thus determining pressure waves of negligible effect. Used setting allows a full closure of the valve in about 45.5 s. In addition, by default settings, the valve has a sensitivity of 0.6%, i.e., it remains inactive for values of Δa<0.6%. Such sensitivity is determined by the intrinsic electro-mechanical accuracy of the valve and of the actuator (i.e., the smallest possible displacement of the shutter according to reduction group and multi-turn device). Notably, this determines the occurrence of a dead-band of the shutter position a with effects of various extent on the accuracy of the pressure regulation.

All the sensors (pressure and flow discharge) were calibrated to provide measurements with time step of acquisition Δt_a of 1 s (that is, measurements of pressure and flow discharge were sent to the PLC on every 1 s). Based on criteria discussed in the previous section and in agreement to results from the literature (e.g., Creaco et al., 2018; Page et al., 2017b), the control time Δt_c for the experiments was fixed to 30 s. The chosen control time is sufficiently high to reduce the number of shutter movements of the control valve, thus assuring adequate lifespan of the valve itself for practical applications. Conversely, high-frequency fluctuations of the pressure signal were disregarded, considering their negligible impact on leakage levels in WDNs. However, an operator of mobile average was used in order to reduce the impact on the control performance of background noise in the pressure signal (pressure fluctuation due to the turbulent flow in the pipe) (Mounce et al., 2012; Campisano et al., 2015). In particular, the value of pressure p_t used for the estimation of e_t was evaluated as average of the ten final pressure values acquired by the PLC during each Δt_c. Mobile average allowed obtaining effective valve control as the regulation was little impacted by random pressure pulses.

In general, the experiments were carried out to explore two main conditions of operation of the pilot system, corresponding to tests conducted *i)* with the ball valve fully open and *ii)* with the ball valve partially closed. Details of the two types of tests are described in the next subsections.

2.3.1. Tests with the ball valve fully open

Modalities to perform such tests are described as follows. Preliminarily, the pump was switched on and the upstream gate valve mounted in the vertical ascending segment of the pipe was fully opened. Contextually, opening of the air purge valves in the whole pipeline allowed purging eventual air pockets residing in the section of interest. Then, the downstream gate valve was adjusted in order to achieve stationary flow conditions characterized by values of flow discharge and pressure at the US close to 9 L/s and to 7 bar, respectively. The set-point value of the CN pressure was fixed to 3 bar for all the tests.

Each RTC test was carried out assuming the plunger valve to be open at the beginning of the experiment. The objective of the tests was to drive the pressure at the CN to the set-point in a relatively quick but gradual way, avoiding over/under-shootings of the pressure and occurrence of oscillations around the set-point.

The tests were carried out with different values of the gain K. A trial and error procedure based on preliminary experiments and simulations with the used model (described later in the paper) was applied to identify the proper range of K values for controller tuning. Accordingly, 5 tests were carried out with K values of 1, 2, 3, 4, and 5. Simulations with the used model were carried out also to investigate the sampling time and to test preliminarily the stability of the scheme with different values of the flow in the pipe (Galuppini et al., 2020).

2.3.2. Tests with the ball valve partially closed

These tests were carried out by closing partially the ball valve in order to determine an energy dissipation that emulates the friction energy losses occurring in the network between the control valve and the remote CN.

The same operational modalities described at the previous subsection were adopted for these tests. However, this time, the partial closure of the ball valve determined a drop down of the initial pressure value at the CN to about 4.5 bar. Globally, also in this case, 5 tests were carried out to evaluate the control performance obtained by use of remote RTC. Preliminary trials and simulations to identify the proper range of K allowed selecting gain values of 1, 3, 5, 7, and 10 for these tests. Sampling time and stability of the scheme under different flow conditions were also investigated.

2.4. Hydraulic model for simulation analysis

The adopted model is based on the use of the equation of the energy conservation and describes the evolution of the process of pressure control as a succession of stationary states. Hypothesis of stationary conditions used for modeling the process at each simulation time step was considered consistent to valve opening/closure speed under RTC, that is low enough to neglect the effects of perturbations of unsteady flow in the system.

The presence of the upstream pump is modeled by means of the head-discharge curve:

$$H = \alpha Q^3 + \beta Q^2 + \gamma Q + \delta \tag{2}$$

where H [bar] is the hydraulic head determined by the pump, Q

[m^3/s] is the flow discharge, and $\alpha = -9.20 \cdot 10^4$, $\beta = -2.05 \cdot 10^2$, $\gamma = 12.96$, and $\delta = 8.49$ are the curve parameters.

The total loss of energy ΔH_{trunk} [bar] determined by the trunk of the adduction pipe (as well as by several singularities from the pump to the section of the US) is calculated globally as:

$$\Delta H_{trunk} = c_{trunk} \frac{Q^2}{2gA^2} \tag{3}$$

where the non-dimensional coefficient $c_{trunk} = 14.7$ was determined experimentally by previous tests carried out under stationary conditions; g [m/s^2] is the gravity acceleration; and A [m^2] is the cross-sectional area of the pipe. Coupled use of Eqs. (2) and (3) allows calculating the value of the pressure p_{us} [bar] at the section of the US, once that the value of Q [m^3/s] is known.

The model evaluates the friction losses in the various pipe segments ΔH_{pipe} [bar] on the basis of the Strickler relationship:

$$\Delta H_{pipe} = 1.01 \cdot \frac{Q^2}{{K_s}^2 D^{16/3}} L \tag{4}$$

where K_s [m$^{1/3}$/s] is the pipe friction coefficient (by Strickler); D [m] is the pipe diameter; and L [m] is the length of the segment.

Moreover, local energy losses due to pipe bends ΔH_{bend} [bar] are evaluated by the model as:

$$\Delta H_{bend} = c_{bend} \cdot \frac{Q^2}{2gA^2} \tag{5}$$

where coefficient c_{bend} is assumed equal to 0.020 (Brater and King, 1976).

Similarly, energy losses $\Delta H_{conv/div}$ [bar] due to the converging/diverging trunks respectively upstream/downstream of the plunger valve are evaluated based on the relationship:

$$\Delta H_{conv/div} = c_{conv/div} \cdot \frac{Q^2}{2gA^2} \tag{6}$$

where $c_{conv/div}$ is assumed equal to 0.010 and 0.025 for the converging and the diverging trunks, respectively (Brater and King, 1976).

The model allows to simulate the effect of the presence of the various types of valves installed in the pipe by considering the flow head loss ΔH_{valve} [bar] generated locally by such devices. The following general relationship is used:

$$\Delta H_{valve} = \xi \cdot \frac{Q^2}{2gA^2} \tag{7}$$

being ξ the valve resistivity to the flow. Notably, $\xi = \xi_{gate}$ for the two gate valves placed in the vertical segments, while $\xi = \xi_{ball}$ for the ball valve. The values of ξ_{gate} and ξ_{ball} were previously determined as a function of their respective opening degrees. The value of the resistivity of the plunger valve $\xi_{plunger}(a)$ was calculated as a function of the valve opening degree a (Fig. 2). Such resistivity value may change on every time step of the simulation Δt_s if the RTC algorithm modifies the value of a.

At each simulation time step Δt_s, the energy conservation equation, together with Eqs. (2)–(7) and Eq. (1), allows to determine flow discharge and pressures in the cross-sections of the pipe in which pressure sensors are installed, thus enabling appropriate comparison with the measurements recorded during the experiments.

For the application of the model, the solution of the system of equations required prescribing the pressure at the downstream outlet of the pilot system. The pressure value at this section was fixed equal to zero since the water freely flows out from the pipe in the recirculation open channel. The value of Δt_s was assumed equal to 1 s (equal to Δt_a) for obvious reasons of comparison between model and experiments.

The solution of the described system of equations is based on the following steps at every Δt_s:

1. An initial value of the flow discharge (unknown variable) is assumed;
2. The pressure p_{us} at the US is calculated by coupled use of Eqs. (2) and (3);
3. Head losses in the pipe are calculated by using Eqs. (4)–(7) and subtracted to the obtained value of p_{us};
4. The head loss due to the plunger valve (Eq. (7)) is determined based on the current value of the opening degree a_t, for times t of the simulation that do not coincide to the control time step Δt_c or to a multiple of Δt_c. Conversely, the same head loss is calculated based on the new value $a_{t+\Delta t_c}$ as obtained by Eq. (1); in this case, the shutter displacement for each Δt_s is determined by taking into account the physical constraints due to the mechanical speed of the shutter.
5. The pressure at the outlet section is calculated, and steps 1–5 are repeated with new flow discharge values until the outlet pressure is equal to zero.

3. Results

3.1. Results of the experiments

3.1.1. RTC tests with the ball valve fully open

The experimental results concerning the RTC tests carried out with $K = 1$ are reported in the graph of Fig. 3. The figure shows measured pressures at both US and CN during the whole experiment. The pressure set-point value is reported in the figure for comparison. The figure also reports values of the flow discharge Q, and of the opening degree a of the plunger valve during the test. Results show that the control algorithm, in this case, allows to achieve the set-point in approximate way since it lowers pressure at the CN from the initial value (about 7.3 bar) down to about 3.5 bar (in about 9 min). The discrepancy between the achieved pressure and the desired set-point depends on the amplitude of the dead-band of the valve shutter, on the adopted value of the gain K, and on the initial opening of the valve. Details on this aspect are deferred to the discussion section.

The CN pressure starts reducing appreciably only about 5 min

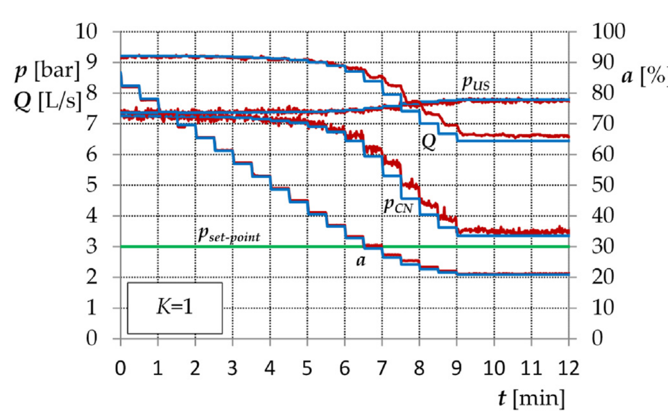


Fig. 3. Experimental (in red) and model (in blue) results concerning the test (ball valve fully open) with $K = 1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

after the beginning of the experiment, that is after that the control system has reduced sufficiently the opening degree of the plunger valve (to about 40% opening). Conversely, during the initial minutes of the test (when the valve is still rather open), the plunger valve does not affect the pressure control process in a significant way. The graph shows the pressure at the CN to decrease by sharp steps occurring synchronically to valve shutter closures; notably, for each displacement of the shutter, the time of action of the valve is about 2 s long, while the shutter remains inactive for the rest of the control time step (for about 28 s). The values of a decrease during time down to about 21% at the end of the test. Due to the increasing energy loss determined by the successive closure steps of the plunger valve, flow discharge circulating in the pipeline decreases from about 9.2 L/s to about 6.5 L/s at the end of the test.

Records at the US shows pressure to increase as the opening degree of the valve decreases (the valve sustains the pressure in the upstream pipe segment). However, pressure increment is relatively small (from 7.3 bar to about 7.8 bar) as the characteristic curve of the pump is rather flat.

Although, in principle, the valve control determines conditions of unsteady flow, the results of the experiment do not highlight the development of pressure waves in the pipeline. Instead, the experiment reveals the presence of “noise” at high-frequency (mainly due to the flow turbulence) that disturbs experimental pressure and flow discharge signals.

Fig. 4a shows the results obtained with $K = 3$. The adopted value of K determines a faster reaction of the control system as compared to the case of Fig. 3, thus allowing a more rapid convergence to the set-point (in about 2.5 min). Incidentally, this time, the set-point is achieved with relatively high accuracy due to a favorable combination of the effects of the dead-band with the used value of K and of the initial valve opening condition. Moreover, as expected, the increased value of K determines steps of a of larger magnitude as compared to previous case. Fig. 4b shows the results obtained with $K = 4$. In this case, the interesting result is that the used K value determines the development of pressure under/over-shooting around the set-point (with the pressure that achieves values down to about 2.5 bar) at the CN. However, after a few oscillations, the system achieves, after about 4.5 min, a pressure value very close to the set-point. Results of the experiments with $K = 2$ and $K = 5$ are not shown in the paper for brevity. As expected, use of $K = 2$ provided intermediate results between $K = 1$ and 3, while use of $K = 5$ further increased under/over-shooting of the pressure.

3.1.2. RTC tests with the ball valve partially closed

Some of the results of the experimental tests carried out with the ball valve partially closed are summarized in Figs. 5 and 6. Fig. 5 reports the results of the test performed using the value $K = 3$. Such value enables direct comparison of the results of this test with those provided in previous Fig. 4a, thus showing the impact of the energy losses determined by the ball valve on the control process. The results show that the RTC system allows leading the initial value of the pressure at the CN (from about 4.5 bar) to the set-point in an accurate way. However, the lower initial value of the pressure at the CN leads to shutter displacement corrections of lesser extent (as compared to Fig. 4a), and therefore to slow down the whole control process (the set-point is achieved in about 9 min). Fig. 5 also shows that the plunger valve closes from 100% to about 23% opening degree, while the flow discharge decreases from about 7.4 L/s down to 6.2 L/s).

Fig. 6a and b report the results of tests obtained with $K = 7$ and $K = 10$, respectively. Both values of K increase significantly the speed of the control action in comparison to $K = 3$. Fig. 6a shows that the set-point value of the pressure at the CN is achieved with relatively high accuracy. Instead, Fig. 6b reveals that the assigned value of $K = 10$ is unsuitably high. In fact, due to an excess of control reaction, the control process shows pressure oscillations to occur. Results of the experiments with $K = 1$ and $K = 5$ are not shown in the paper. However, while the adoption of $K = 1$ provided unsuitably slow reaction of the controller, results with $K = 5$ are intermediate between those obtained with $K = 3$ and $K = 7$.

3.2. Simulation results

3.2.1. Simulation of RTC experiments with the ball valve fully open

In addition to the results of the experiments, the previous figures report the corresponding results obtained with the simulation model. Simulation with $K = 1$ (Fig. 3) shows very good agreement between numerical and experimental results concerning the pressure values at the US. Slight differences in the pressure values are observed at the CN during the closure stage of the plunger valve (for values of a<30%). The figure shows that the model performs well also in the evaluation of the flow discharge (with simulated values of Q being slightly smaller than the measured values). An excellent agreement of simulated and measured pressure values is obtained at the US for the simulation with $K = 3$ (Fig. 4a); only minor differences between model and experimental results are observed at the CN during the control process (for values of a between 30% and 40%). In general, although the control action is much faster in this test than in the test of Fig. 3, the model is able to interpret well the whole control process also in terms of flow discharge and opening degree of the plunger valve. The results plotted in Fig. 4b (K=4) highlight the steady-state model capability to simulate correctly also the development of pressure over/undershooting. The simulated curve of a fits almost perfectly the measured values during both the initial closing stage and the successive phases of opening/closure of the valve shutter before the set-point achievement.

Globally, the analysis of the results for all the tests shows that use of the hypothesis of steady-state allows to reproduce in a good way both pressures and flow discharge in the system. Table 1 reports (for all the tests) the value of the root mean square deviation (RMSE) between observed and simulated values of pressure at the CN and flow discharge for the whole test duration.

The table shows that, RMSE values are in general relatively small, thus confirming that the model is sufficiently good in describing correctly the whole control process evolution. A separate case is represented by the test carried out with $K = 5$ for which the worst agreement between model and experiments was obtained (RMSEp_{CN} = 0.875 bar), because of the occurrence of pressure oscillations during the experiment.

3.2.2. Simulation of RTC experiments with the ball valve partially closed

Figs. 5 and 6 report the simulation results for $K = 3$, $K = 7$ and $K = 10$, respectively. Fig. 5 shows a good agreement of simulations with the experiments. Similarly to the case shown in Fig. 3, the curve of a tends to provide simulated values slightly smaller than the experimental ones; correspondingly, the simulated flow discharge decreases earlier than the experimental flow discharge. However, the value of a achieved at the set-point condition is well captured by the model. Similar considerations can be carried out for the test shown in Fig. 6a (K=7). The curve of the flow discharge shows the model to provide differences with the experiments for values of a close to 30%; in addition, small differences between model and experiments are observed in the final stage of the control process. Also Fig. 6b (K=10) shows that model and experiments agree very well for the first 2 min from the beginning of the test; instead, the model tends to amplify oscillations around the set-point occurring in the final stage of the control process. Table 2

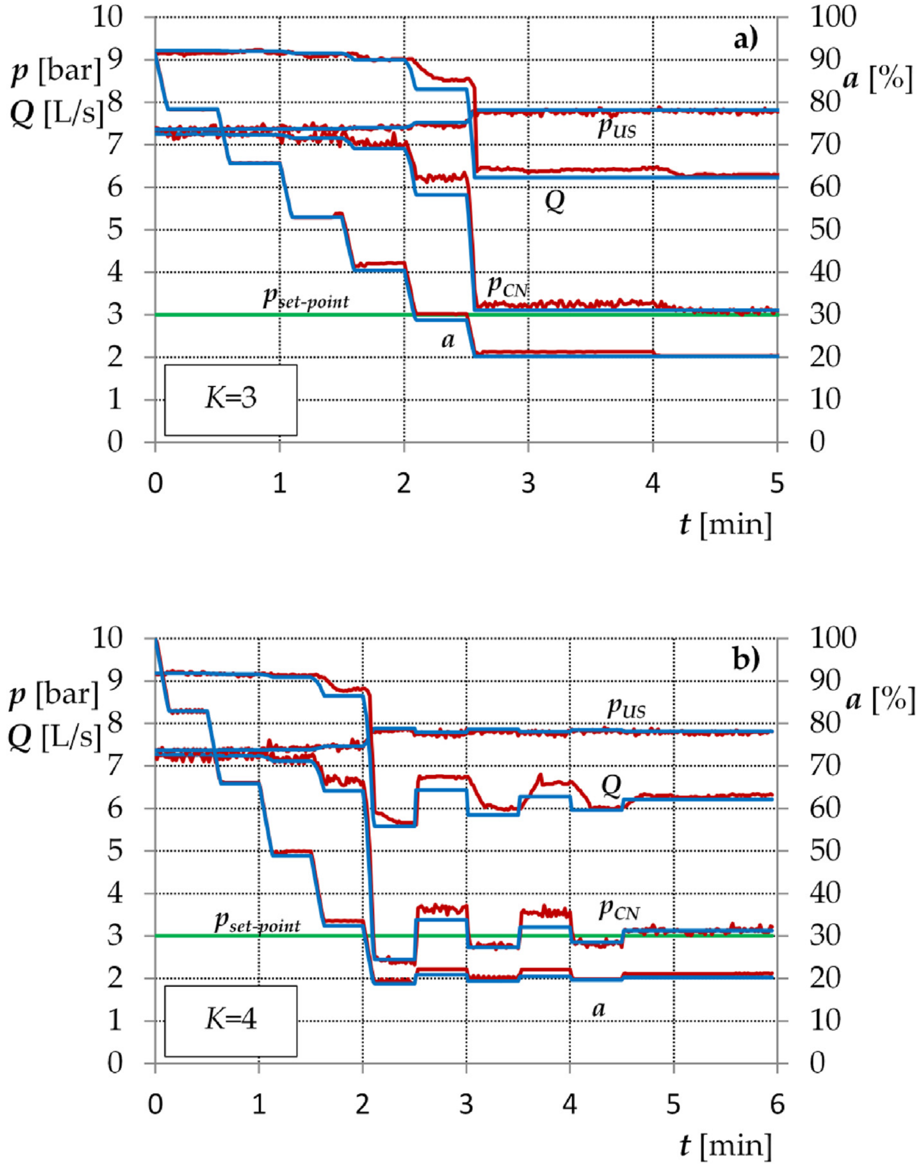


Fig. 4. Experimental (in red) and model (in blue) results concerning the tests (ball valve fully open): (a) with $K = 3$; (b) with $K = 4$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

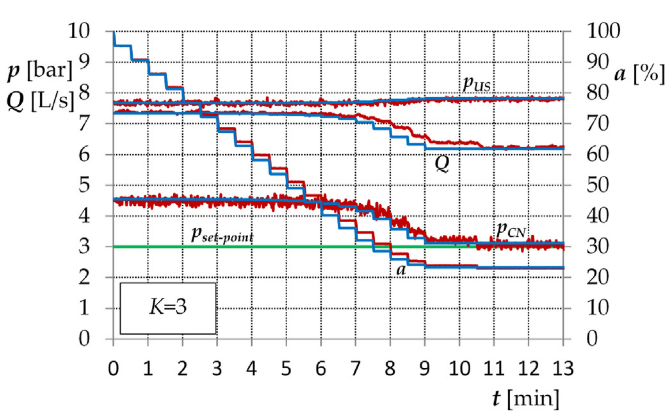
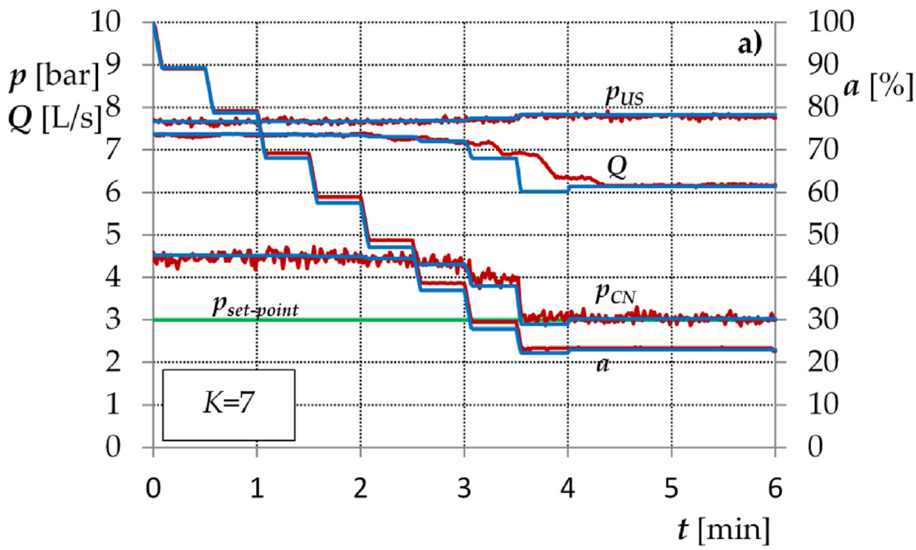


Fig. 5. Experimental (in red) and model (in blue) results concerning the test (ball valve partially closed) with $K = 3$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

summarizes main results for all the tests carried out with the ball valve partially closed. The table reports values of RMSE rather similar to those of Table 1, thus highlighting that the model performance is not affected significantly by the energy dissipation due to the ball valve.

4. Discussion

The obtained results demonstrate the potential of application of closed-loop remote RTC schemes for pressure control in the pilot system. The larger costs of installation/operation of closed-loop remote RTC systems in WDNs would be balanced by an expected increase in pressure control performance due to the real time use of pressure measurements. In this concern, closed-loop schemes may take also advantage of use of models that may allow improved tuning of the regulator and design of the behaviour of the system. Specifically, use of simulations can allow verifying the stability and performance of the control system in a wide range of conditions



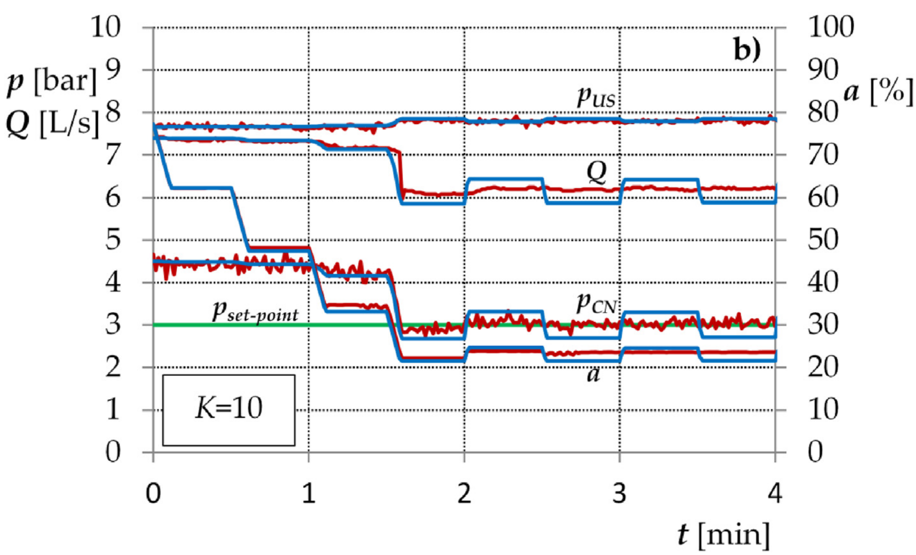


Fig. 6. Experimental (in red) and model (in blue) results concerning the tests (ball valve partially closed): (a) with $K = 7$; (b) with $K = 10$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Tests with the ball valve fully open. Comparison between simulation and experimental results in terms of values of RMSE.

K	RMSEp_{CN} [bar]	RMSEQ [L/s]
1	0.190	0.187
2	0.138	0.203
3	0.169	0.219
4	0.169	0.241
5	0.875	0.944

Table 2
Tests with the ball valve partially closed. Comparison between simulation and experimental results in terms of values of RMSE.

K	RMSEp_{CN} [bar]	RMSEQ [L/s]
1	0.166	0.127
3	0.133	0.141
5	0.139	0.064
7	0.127	0.211
10	0.238	0.227

before field implementation.

It has to be stressed that the RTC system scheme adopted for the experiments is relatively simple as compared to control architectures that might be required for pressure regulation of complex WDNs (that are likely to include multiple controllers and multiple control nodes). Therefore, the validity of the obtained results remains confined to the conditions and to the range of values of the parameters considered for the laboratory experiments.

Globally, the experiments show that, under appropriate calibration, the RTC system is able to adjust valve actuators in order to obtain proper control of pressure at the control node. In this concern, the results of the experiments deserve specific discussion. As shown by the analysis, the time needed to converge to the set-point is affected by the used value of K. Although the plunger valve at the beginning of the experiments was open (this is the most disadvantaged condition to achieve the set-point), the results show that time to drive the system to the set-point is always in the order of a few minutes, for any values of K. This would demonstrate potential for adequate response of the RTC system in controlling pressure of real WDNs (where variations of the average water demand are typically much slower).

The tests conducted with the ball valve partially closed required values of K normally larger than those required for the tests with the ball valve fully open. This result reveals the impact of the energy losses determined by the ball valve on the controller calibration. In fact, all initial conditions being equal, pressures at the CN are always smaller when the ball valve is partially closed; this determines smaller deviations from the set-point and (as a consequence of the used algorithm) the need of using larger values of K to obtain a sufficiently quick reaction. This finding confirms the literature results that show that controller calibration is site-specific and is markedly affected by the geometrical and hydraulic characteristics of the WDN (e.g., by pipe friction losses between the site of the control valve and the site of the control node).

The analysis of the performance of the RTC system includes the evaluation of the accuracy of the control algorithm in converging to the set-point. As already introduced in the previous chapter, the results of the experiments reported in Figs. 3–6 point out that the accuracy of the control algorithm in driving the system to the set-point depends on different parameters, including the valve shutter dead-band, the initial valve opening condition, as well as the adopted value of K. Also introduction of filters such as the used procedure of pressure moving average may affect the performance of the closed-loop (Galuppini et al., 2019). In absence of dead-band, the adopted algorithm (Eq. (1)) coincides with a standard integral control algorithm. Remarkably, due to the presence of background noise in the pressure signal, both algorithms would determine continuous opening/closure displacements of the valve around the set-point. Therefore, the adoption of a dead-band in the control is somehow necessary to reduce ineffective displacements that can unusefully undermine the life of the valve. When the dead-band intervenes on the control action (that is usually when the pressure approximates the set-point value and calculated values of Δa are small), the two algorithms behave differently. Specifically, Eq. (1) forces the valve to stay stably inactive until $\Delta a < 0.6\%$, with an unavoidable (but stable) error of the pressure with respect to the set-point (as shown in a clear way in Fig. 3, for example). Instead, a standard integral controller would continue cumulating errors in the pressure, ultimately leading the control system to circumvent the dead-band; under this condition the system may determine frequent valve opening/closure displacements, with consequent pressure fluctuations around the set-point.

In line of principle, replacing the dead-band acting on the control signal with one acting on the pressure signal would increase the ease of calibration and the quality of the control (it would sum zero errors to the integral action when the measured signal is within the dead-band) (Tian and Tao, 1997; Galuppini et al., 2018). However, control inaccuracy due to the intrinsic precision of the valve mechanics cannot be avoided. Therefore, based on previous remarks, the value of the sensitivity of the valve with use of Eq. (1) should be small enough to approximate well the set-point but sufficiently large to reduce the impact of high-frequency pressure pulses on the control action.

Another point of discussion concerns the dynamics of the control action. The experiments have confirmed that any excess in the value assigned to K gives rise to unsuitable control characterized by the development of permanent pressure oscillations around the set-point. Side to the bad pressure control, permanent oscillations might condemn the control valve to continuous opening/closure displacements in the attempt to lead the system to the set-point. Therefore, it is suggested to discard high values of the gain K in the calibration stage although this might go to detriment of the promptness of the control reaction. Notably, in the experiments that were carried out, values of K in the range 2–3 and in the range 5–7 are suitable to obtain a performant control of the plunger valve for the two sets of experiments described at sections 3.1.1 and 3.1.2, respectively.

Simulations carried out in this paper confirmed the suitability of schematizing the pressure control process as a succession of steady-state conditions for all the experiments. In fact, although real time pressure control generates conditions of unsteady flow, relevant effects in terms of development of pressure waves in the experimental pipeline were not detected. Such a result is determined by the relatively small speed of the valve shutter that provides times of opening/closure displacements that are much larger than the characteristic travel time of pressure waves in the experimental pipeline. Remarkably, implementation and related simulation of remote RTC in real WDNs (where travel times are much longer) could require to set the speed of the valve shutter differently. Proper setting must assure both limitation of the magnitude of pressure waves and sufficient reactivity of the control system. Also, the increase in the value of the control time step may be required in order to assure that transients resulting from the adjustments of the valve would disappear between successive regulations (Galuppini et al., 2020). In support of this, Creaco et al. (2017), by comparison with results of unsteady flow modeling, confirmed that the assumption of stationary conditions with proper values of the control time is adequate for RTC applications focusing on leakage reduction in WDNs.

Although, globally, good results were obtained with the model in reproducing the experiments, the results summarized in Tables 1 and 2 reveal that the increase in the value of the gain may go at detriment of model predictive performance. For instance, Fig. 6b shows that the highest value of the gain (K=10) determines larger overshoot/undershoot of the pressure as compared to the experimental measurement when the system is close to the set-point. This result reveals that the discrepancy between model and experiments is unavoidably amplified by the high values of the gain that acts as multiplier of the pressure deviation from the set-point.

5. Conclusions

In this paper, the results of experiments carried out in a laboratory pilot system were analyzed in order to show potential for application of remote RTC in controlling pressure in WDNs.

Remote RTC was applied to control the pressure in the pilot system by adjusting in real time the opening/closure of a motorized plunger valve based on remote measurements of pressure acquired in real time. An integral-type algorithm was considered for the implementation of the closed-loop control of the valve. A numerical model of the laboratory system was used for the preliminary setup of the pilot and for the simulation of the pressure RTC process.

Main results of the analysis include the following points:

- the experimental tests have shown that, under appropriate calibration, the considered remote RTC architecture allows for effective control of the pressure in the pilot system. This result opens research perspectives to further test remote RTC systems for leakage management in real WDNs using architectures of closed-loop control; thanks to the limited speed of the valve shutter action, non-stationary effects in terms of development of pressure waves during the experimental tests in the pilot system were proven negligible; however, the transferability of the RTC system to real WDNs could require limiting further the valve speed due to the expected longer wave travel times;

- proper RTC implementation in the field may require to increase the value of the control time to assure that the valve control would not be affected by eventual pressure wave reflections; longer control time steps in the order of few minutes and adoption of a dead-band for small valve displacements may allow also limiting the number of valve openings/closures during the 24 h, thus increasing the valve life without reducing the system effectiveness in leakage control;
- the experiments revealed that appropriate values of K may assure a performant control, with values of the achieved pressure and of the system reactivity compatible with the objective of water leakage reduction in WDNs. Smaller values of the gain K may be required in field applications in relation to the potential increase in the control time;
- the simulations revealed the suitability of schematizing the pressure control process as a succession of steady-state conditions for all the experiments. Comparison between model and experiments showed high values of K may decrease the model predictive performance. Subject to proper selection of control time, use of the proposed simulation approach may allow the evaluation of benefits of remote RTC implementation in the reduction of leakage in WDNs. Models based on the steady-state hypothesis can also be of help for the preliminary design of the control system in WDNs.

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CRediT authorship contribution statement

Alberto Campisano: Conceptualization, Investigation, Methodology, Writing - review & editing. **Carlo Modica:** Conceptualization, Investigation, Methodology, Writing - review & editing. **Fabrizio Musmeci:** Investigation, Software. **Camillo Bosco:** Software. **Aurora Gullotta:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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