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A lab prototype of pressure control in water distribution networks

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Abstract:
A common strategy for leakage reduction in Water Distribution Networks (WDNs) is the use of Pressure Reducing Valves (PRVs). As well known, a relationship between pressure and water losses can be established, according to which reducing pressure results in reduced losses. In many cases pressure is greater than the minimum required for adequate service level, because of the variability of flow and pressure within the WDN. To increase the effectiveness of PRVs, a Real Time Control (RTC) of the regulated pressure can be developed, as pointed out by many researchers. Consequently, in the paper the issues arising from pressure RTC in a WDN is discussed. Laboratory experiments were carried out to assess the capability of the controller to achieve the set point pressure, regardless of the inlet conditions. A numerical model was also developed, showing good agreement with experiments.

Keywords: Water distribution systems, water losses, Pressure Reducing Valves, real time pressure control.

1. INTRODUCTION

Nowadays, management and reduction of the water losses in Water Distribution Networks (WDNs) assume more and more importance, also because of the current trend to emphasise environmental protection and sustainability of consumptions. To this aim, in last decades, one of the main concerns of the water system managers has been the minimisation of water losses, that reach values in the order of 40% (or even more) (Araujo et al. (2006)). Numerous studies also showed that leakage in water supply networks strictly depends on the deterioration and age of pipes and devices (Council (1980)). Telemetry systems have long been used in large WDNs for improving the real-time monitoring of quantity and quality parameters. As monitoring technologies evolve, new possibilities for controlling and managing complex infrastructures such as water networks arise.

In order to reduce leakage, control strategies arising from the relationship between leakage and pressure in pressurized pipes have been widely used. Such strategies are mainly based on the use of Pressure Reducing Valves (PRVs) for pressure regulation. PRVs are usually installed at the inlet of a District Meter Area (DMA), so as to reduce pressure level over the district and, consequently, water losses. In other cases, PRVs can be deployed within a WDN. PRVs are set to regulate pressure within the network by ensuring a minimum pressure at all nodes. To this aim one (or more) disadvantaged nodes of the network can be identified, at which the pressure should be kept greater than the minimum value. Such node(s) can be identified by means of pressure measurements or numerical models, whereas the minimum pressure to be guaranteed can be assessed according to the network characteristics. A number of studies can be found in the literature, aiming at optimizing both location and setting of PRVs (see Jowitt and Xu (1990); Reis et al. (1997); Vairavamoorthy and Lumbers (1998); Wright et al. (2015)). Araujo et al. (2006) proposed a two-steps methodology, simulating each valve as an additional pipe roughness. The first objective function optimizes the number and the location of valves, whereas the second is used for the adjustment of the valves opening degree. Nicolini and Zovatto (2009) formulated the determination of the number, location, and setting of PRVs as a two criteria optimization problem, by minimizing the number of the valves and the total leakage in the system.

The optimization process requires knowledge of the temporal and spatial distribution of water demands. However, when these differ from assumptions, the solution found by such models using a fixed regulation of the PRV may no longer be effective. To this aim, a Real Time Control (RTC) of the PRV can be used, so as to ensure the optimal pressure level over the network, regardless of the operating condition. While remote control of valves, pumps and other devices has been widely used within supply and distribution system in the last decades, very few applica-

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tions have been developed for PRVs and pressure control, and the greatest part of them only from a theoretical point of view. Examples of regulation by real-time control techniques have been largely adopted in the field of urban drainage systems during the last decades (Schutze et al. (2004), Schilling (1994), Pleau et al. (2005)). In these papers valve settings can be regulated in real time according to time varying pressures at network nodes. Specific probes acquire distributed pressure measurements in the network at each time step; then the acquired data are transferred to logic controllers which adjust the valve settings to guide system pressures to the desired set-point values, checking it not only in simulation environment but also in lab tests. Berardi et al. (2015) pointed out the advantages of a remote RTC against a local RTC in terms of pressure and water losses reduction. Diaz Vela (2014) proposed a methodology for pressure control in WDNs which integrates: the network model; a simplified valve dynamics; and a stochastic demand model. Campisano et al. (2012) presented a general method to calibrate the proportional controllers for the RTC of motorized pressure valves in WDNs to reduce leakage during ordinary operation. Campisano et al. (2016) also proposed a field-oriented methodology for implementing RTC for leakage reduction in a WDN. Numerical simulations were carried out on a Norwegian WDN, showing the benefit of the control in terms of leakage reduction under different scenarios. In the abovementioned studies, steady state conditions were considered, i.e. very slow movement of the valve was assumed, so as to neglect pressure transients due to the valve operation. Nevertheless, field and laboratory experiments showed that PRV regulation cannot be represented as a sequence of steady states, because of the pressure oscillation arising during regulation. As an example, Ulanicki and Skworcow (2014) discussed the violent pressure oscillations at the PRV outlet at low flows, and Meniconi et al. (2015) showed the transient following the regulation of a PRV. A dynamic model of the PRV is thus required in case of RTC. Prescott and Ulanicki (2003) developed the mathematical model of a PRV. The model was developed in a Simulink environment, and thus is less adequate for field applications. A simpler model could be more effective for porting to a Programmable Logic Controller (PLC), which commands the PRV.

The influence of water transients in networks supplied through PRVs, such as sustained or slowly decaying oscillation and large pressure overshoot, was investigated by Prescott and Ulanicki (2008). The model demonstrated that the response of the system to changes in demand can produce large or persistent pressure variations, similar to those seen in practical experiments. A proportional-integral-derivative (PID) control mechanism was proposed to replace the existing PRV hydraulic controller, showing the significant improvement of the network response. The approach was further improved by Ramirez-Llanos and Quijano (2009), which proposed some bioinspired approaches in order to increase the robustness.

Nevertheless, field (or even laboratory) applications of RTC in WDNs are still very uncommon, because of the major difficulties arising from both the communication system and the need of adequate control strategies. Thus in this paper we aim at: (i) identifying a simplified dynamic model of a PRV; (ii) developing a PID controller for the closed-loop control of the pressure at any monitored node; (iii) discussing the issues arising from the RTC of the pressure at a node within a WDN. Laboratory experiments were carried out to identify a simple PRV model and to assess the capability of the controller to regulate pressure at a network node, also in case of abrupt variation of operating conditions.

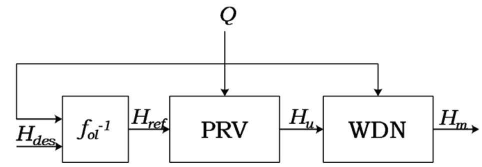

Fig. 1. Open loop controller of a WDN

2. REAL TIME PRESSURE CONTROL IN A WDN

Let us consider a PRV located at the inlet of a (district of a) WDN. The PRV is activated by an electric signal having a one-to-one correspondence with the desired output pressure, i.e. any desired output pressure has a corresponding voltage input to the valve. Consequently, for the sake of simplicity, h_{ref} will be used in what follows as input signal to the PRV. Hence the PRV receives as input h_{ref} and gives as output the pressure head h_{u} (or equivalently input is the desired total head $H_{\mathrm{ref}}=h_{\mathrm{ref}}+z_{\mathrm{PRV}}$, and the PRV output is the head $H_{\mathrm{u}}=h_{\mathrm{u}}+z_{\mathrm{PRV}}$, z_{PRV} being the PRV elevation). The flow discharge Q acts on the valve as a disturbance input since it cannot be controlled.

The head H_{u} at the valve outlet is the input to the WDN, whose output is the head at some "monitored node" H_{m}. In order to ensure adequate service level and minimize leakage within the WDN, the head at this selected node should be kept constant at a desired value H_{des}. Such desired minimum value can be assessed according to the network characteristics (elevation, topology, discharge, etc.).

A common approach to control pressure in WDNs is an open loop strategy, as in Fig. 1. With a feed-forward controller it is possible to choose the reference value for the PRV input as a function, parameterized in Q, H_{des}, of the desired head at the monitored node ($H_{\mathrm{ref}} = f_{\mathrm{ol}}^{-1}(H_{\mathrm{des}}; Q)$). The head upstream of the network can also be switched among two or more pre-selected values, according to the flow discharge Q entering the network in certain day intervals. This open loop controller only requires the PRV and (possibly) a scheduler to change the set point during the day. However, such a controller cannot handle effectively large variations of Q. Moreover, the function f_{ol}^{-1} is difficult and uncertain to determine. Therefore even though the open loop controller is technologically simple, it can yield a slow and imprecise behavior; a feedback action can help to obtain a faster and more robust working of the system instead. Hence, it is natural improving the controller performance with the closed loop strategy in Fig. 2.

Nevertheless, when regulating pressure in a WDN some constraints have to be taken into account: first the PRV cannot provide more pressure than its upstream head and second the head variation at the monitored node is felt with some finite delay τ, because of the finite propagation

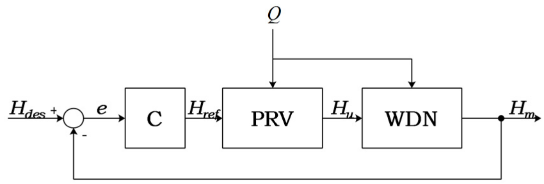

Fig. 2. A closed loop control scheme

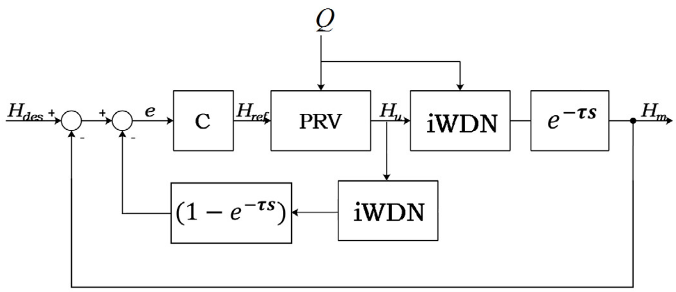

Fig. 3. The Smith's predictor scheme to cope with finite delays.

velocity of pressure waves. In particular such delay can amount also to many seconds, according to pipe material and the distance between the PRV and the monitored node. Thus, one of the most important issues related to a feedback control is that it can generate oscillations and even instability in the presence of actuator saturation and transport delays. We deal with these issues by applying a Smith's predictor to the pressure closed loop controller, see Fig. 3. We assume the real WDN can be described by the (information) cascade of an ideal WDN (iWDN), where pressure transient propagates instantaneously (i.e., with zero delay), and a finite delay block, which delays input signals by τ seconds. With this scheme the time delay is taken outside of the control loop in the transfer function relating process output to setpoint.

3. LABORATORY SET-UP

Experiments were carried out at the Hydraulic Laboratory of the Department of Civil, Architectural, and Environmental Engineering of the University of Naples Federico II in Naples, Italy. The four loops network described by Fontana et al. (2016) was used for experiments. The network is supplied by a pump, which delivers a flow discharge up to 45 l/s at a maximum pressure head around 70 m. An air chamber is located at the network inlet, so as to avoid pressure and flow fluctuations during experiments. The network is made of cast iron, with nominal diameter 150 mm. Small segments of steel are also used for ease of installation. A total of 19 motorized gate valves are installed for flow control, actuated with electric actuators for opening and closure. Flow discharge can be regulated by means of manual valves located at 3 outlets. 11 pressure transducers and 7 flow meters are also deployed within the network for complete flow characterization. A new pipeline was added to the network, where the PRV and a flow meter were installed (Fig. 4). Only the thick line in Fig. 4 was used for experiments. Consequently, some of the motorized gate valves were left closed. Flow discharge was varied by means of the outlet valve at the lower left corner of the network.

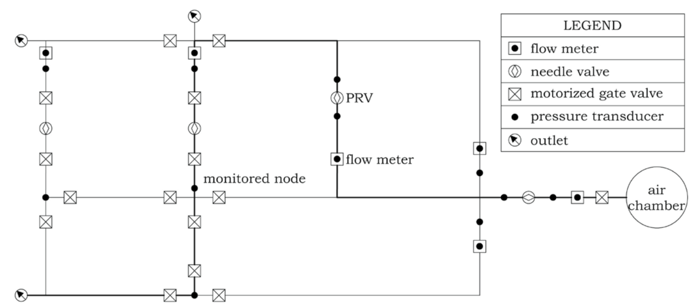

Fig. 4. Sketch of the laboratory network.

The PRV is a Bermad valve, Mod. EN 720 4SE - VI. The valve is equipped with a motorized pilot with input voltage between 0 V and 10 V, thus allowing to remotely regulate the outlet pressure. According to the input voltage, an actuator compresses or stretches the pilot spring, thus varying the outlet pressure. Input voltage of 0 V corresponds to the maximum outlet pressure, whereas an input voltage of 10 V corresponds to the minimum outlet pressure (ideally, closed valve). A flow meter Mod. G2 PMAG for precise flow measurement was also installed. Two pressure transducers (Mod. WIKA S-11), with a pressure range of 0–10 bars and accuracy of 0.25% were also installed, upstream and downstream of the valve. Data were collected by a Programmable Logic Controller (PLC) and sent to a System Control And Data Acquisition (SCADA) for visualization and storage. Sampling interval for data storage was varied between 0.11 s and 1 s, depending on the temporal resolution required by the experiment.

4. MODEL IDENTIFICATION

In order to identify a suitable model to characterize the PRV and WDN behavior, a number of laboratory experiments were run. As said before, the PRV is activated by an electric signal having a one-to-one correspondence with the desired output pressure. Steady state and transient behaviors of the PRV have been identified by varying the voltage input to the valve.

4.1 PRV steady state behavior

A number of experiments were carried out in order to characterize the steady state PRV behavior at varying inflow discharge Q and supply pressure head h_s, by first setting the initial flow discharge at fully open valve Q_{fo}, then increasing the input voltage (which leads to a reduction of the pressure at the valve outlet). The input voltage was set to 0 V at the beginning of each experiment and then progressively increased by 0.25 V at each step. When the downstream pressure was lower than 1–2 m, the experiments were ended.

Fig. 5 presents the steady state pressure head downstream of the valve h_u at varying input voltage and flow discharge. Note that pressure is expressed in meters of water column. Plotted data exhibit an effective range of input voltage up to $\sim$ 7 V and it can be noticed that the outlet pressure is flat for input voltage smaller than $\sim$ 3 V. Indeed no regulation is performed for voltage smaller than $\sim$ 3 V, because the regulated pressure would be greater then h_s.

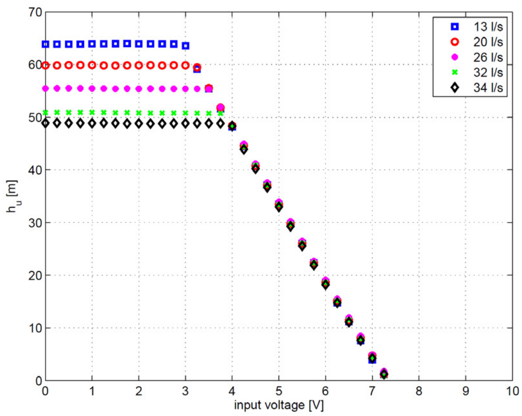

Fig. 5. Pressure at the valve outlet at varying input voltage and flow discharge.

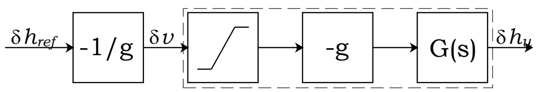

Fig. 6. PRV block.

For such values, the pressure at the valve outlet is the supply pressure minus the head loss within the valve, in the order of 3–4 m. The experiments show that such a constant value varied according to the inflow discharge, since a centrifugal pump supplies the laboratory circuit: the greater the flow discharge, the smaller the head given by the pump (and so h_s). Instead, in the range of input voltage effective for pressure regulation, the valve exhibits a linear behavior and a linear relationship can be derived between the input voltage variation and the regulated pressure variation: $\delta h_u = -g\,\delta v$, with the slope $g = 14.6$ m/V.

Fig. 6 shows this relationship within the entire PRV block. Note that actually the model does not take into account the offsets, and this issue is solved by translation of the axes around the working point $\bar{h}_{ref}$, $\bar{v}$, $\bar{h}_u$, i.e. setting $h_{ref}(t) = \bar{h}_{ref} + \delta h_{ref}(t)$, $v = \bar{v} + \delta v(t)$, $h_u(t) = \bar{h}_u + \delta h_u(t)$.

However, a small influence of Q and h_s on the steady state regulated pressure came out from experiments, because of mechanical nonlinearities and hysteresis embedded in the PRV operation. Hence, the valve exhibits slightly different steady state outlet pressures for the same input voltage, depending on the flows characteristics and also on the input voltage step height. An example is reported in Fig. 7, where, given a step from 4.0 V to 4.5 V as input voltage, slightly different values of pressure at the valve outlet h_u are obtained, at varying the flow discharge. Such offsets can be described as unknown disturbances on the PRV pressure outputs

4.2 PRV dynamic behavior

Data also show the dynamic behavior of the valve. In order to characterize the PRV dynamics, a simple model is required for real time operation, and preliminary analysis showed that the step response of the valve is quite well represented by the step response of a second order linear model. The PRV model was obtained by giving a step

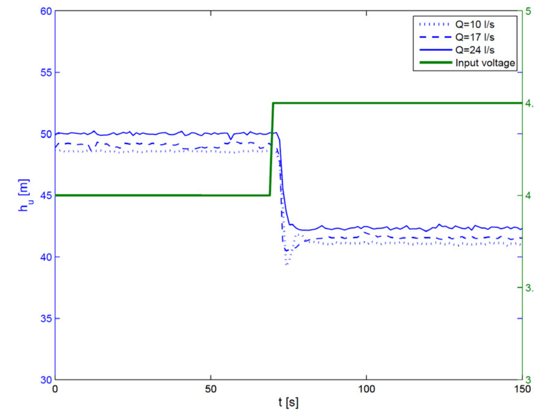

Fig. 7. Pressure at the valve outlet at varying flow discharge and input voltage

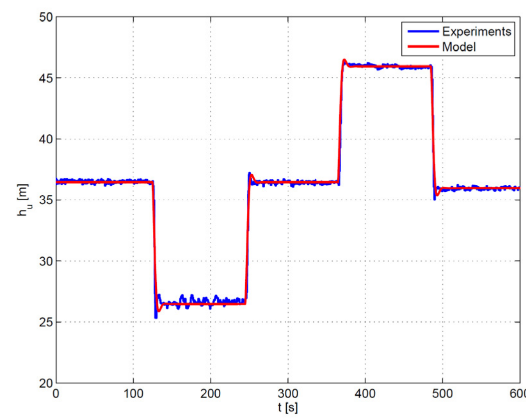

Fig. 8. Experiments and identified PRV model for a sequence of step inputs.

voltage as input $\delta v(t)$ and observing the output pressure $\delta h_\mathrm{u}(t)$. Namely the following sequence of the input voltage was used: 4.9 V - 5.5 V - 4.9 V - 4.3V - 4.9 V. The Matlab identification toolbox was used for identification, which returned a fit of 94%. Results were plotted in Fig. 8, and the identified transfer function $G(s)$ in Fig. 6 is:

$$G(s) = \frac{0.253}{s^2 + 0.672s + 0.253}.$$

having undamped natural frequency $\omega_n = 0.503$ rad/s and damping ratio $\xi = 0.668$.

Results showed the good agreement between experiments and model, only slight differences can be found during some transients, and both rise time and fall time are well reproduced. In order to assess the reliability of the model for different operations, the same parameters were used for a different range of step inputs. Experiments and PRV model results were plotted in Fig. 9, showing again a satisfactory fitting and greatest differences only for very large step heights, whereas a better agreements was found for smaller pressure drops.

4.3 WDN model

The controller also requires the WDN to be modeled. Distributed and concentrated head losses occur, resulting in a head drop $\Delta H = H_\mathrm{u} - H_\mathrm{m}$ between the PRV outlet

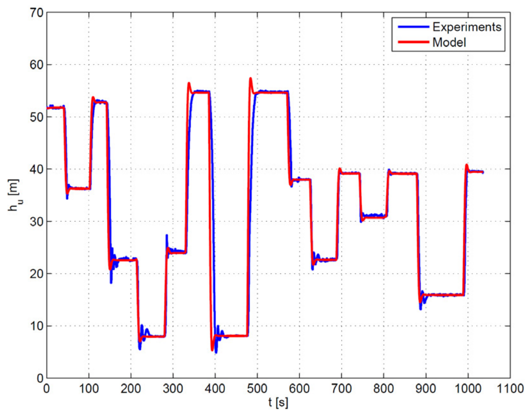

Fig. 9. Reliability of the PRV model for different operations

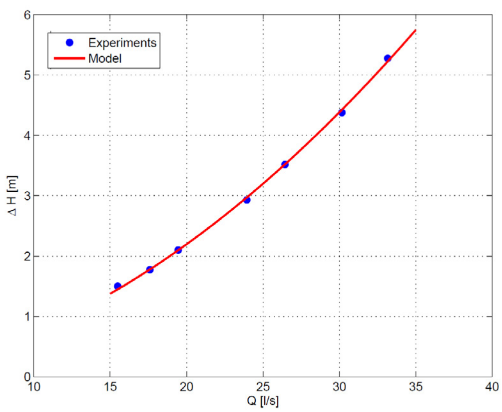

Fig. 10. Head losses between PRV and monitored node at varying flow discharge in the laboratory network.

and the monitored node. In general, head losses mainly depend on the upstream flow Q, but also on the network topology, the distribution of Q within the network, etc.. Because of the simple flow pattern, for the laboratory network, head loss only depends on Q. Head drop between the valve outlet and the monitored node was measured at varying flow discharge (Fig. 10) and interpolar quadratric relationship was inferred from experiments (continuous line in Fig. 10).

5. TEST OF CONTROL STRATEGIES

The model of the PRV identified in the previous paragraph was used to assess the capability of an integrative controller $C(s) = \frac{k_i}{s}$, with gain $k_i = -0.005$ for the pressure regulation in a WDN. In order to assess whether the controller is able to regulate the pressure at the monitored node in different operating conditions and the model properly predicts the pressure transient at the monitored node the control strategies were tested considering step inputs with set point set to 25 m, 35 m, and 45 m. We compare experiments with simulations for the following strategies: *i*) closed loop controller in Fig. 2 without delay; *ii*) closed loop controller in the presence of transport delay; *iii*) closed loop controller with Smith predictor in Fig. 3. Results obtained with the first control strategy are plotted in Fig. 11, showing the good

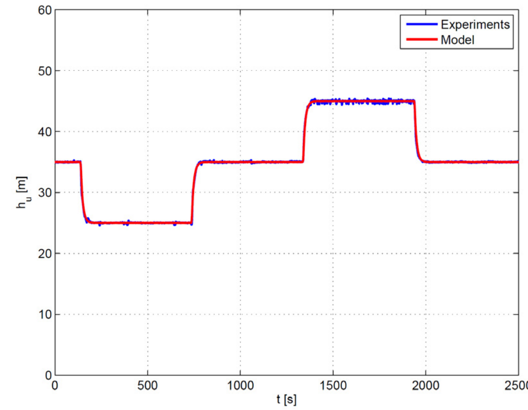

Fig. 11. Closed loop controller for pressure control at monitored node.

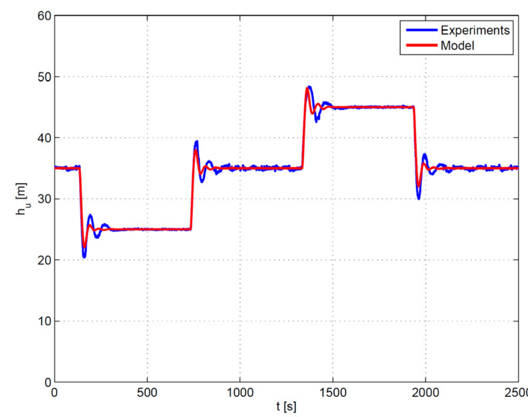

Fig. 12. Closed loop controller for pressure control at monitored node with delay $\tau = 9$ s.

agreement between experiments and model. Because the head variation at the monitored node is felt with some finite delay τ, experiments were carried out to quantify the effects of such delay on the pressure control. Since the distance between the PRV and the monitored node in the laboratory network is quite short (in the order of a tens of meters), the delay was simulated by shifting of τ s the acquisition of measured pressure. In the experiments a 9 s delay was considered, since it was supposed to be a reasonable choice for medium-sized field applications.

To prevent the destabilizing effects of time-delays on the closed-loop dynamics, a good measure of the stability margin in this case is the delay margin, which is the smallest time delay required to make the system unstable. The phase margin of the closed loop system here is measured at the crossover frequency $\omega_c = 0.068$ rad/s and is equal to $\phi_m = 79.6°$, so that the delay margin is ~ 20 s. In Fig. 12 the pressure measured at the monitored node was plotted with the simulations and results show again a good agreement with experiments. We noticed that for greater gain values, differences are more significant, although the model is able to properly identify the frequency of oscillations. Experiments confirmed that, in case of finite delay, the system is not able to reach the set point pressure at the monitored node and undamped oscillations may arise for greater gains. A way out of this problem is slowing

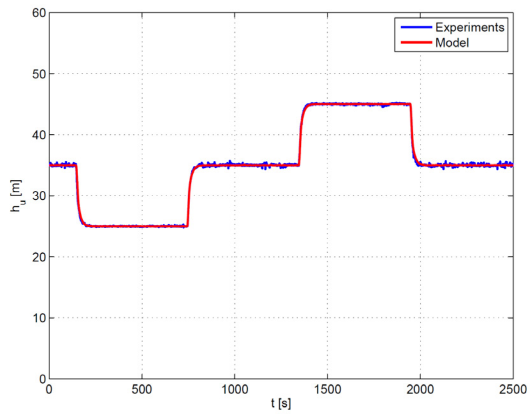

Fig. 13. Closed loop controller with Smith predictor for pressure control at monitored node with delay $\tau = 9$ s.

down the control reactions and thus accepting a reduction of dynamics performance by choosing smaller values of the integrator gains. Otherwise, as said before, another possible solution to problems related to the finite delay is given by the Smith's predictor scheme in Fig. 3. Results of this control strategy at the monitored node are given in Fig. 13. Measured and simulated values exhibit no oscillation and pressure regulation can be performed with a very regular pattern, as for a closed loop controller without delay.

6. CONCLUSIONS

A lab prototype of pressure control was investigated in the paper. Pressure was regulated at a monitored node of the network, by regulating the outlet pressure of a PRV. A simplified model of this valve was identified, so as to represent the valve behavior at varying input setting. A model of the laboratory network was identified too. Results showed that simulations are in very good agreement with experiments. Experiments showed the capability of the proposed control strategy to regulate the pressure at a monitored node. The issue relating to the transport delay occurring in real environments was taken into account too, showing the oscillations and instabilities which may arise for large values of the gain. To this aim, the effectiveness of the Smith predictor was also assessed.

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