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Leakage management: WDNetXL Pressure Control Module

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Abstract

A WDNetXL Pressure Control module to support planning and real-time functioning analysis of Remote Real Time Control (RRTC) devices is here presented. RRTC devices allow the optimal background leakage reduction by maintaining a constant value of pressures into the network. In fact, RRTC devices tune their action (e.g., opening degree of a shutter) by maintaining a target pressure value at the hydraulically critical control node. The key idea is that the pressure variation at critical node is influenced by the water distribution network behavior over time and, then, the RTTC devices are modulated accordingly. The communication technologies allow the real-time transfer of pressure readings from remote/critical nodes to PLC units driving the devices. Furthermore, the WDNetXL Pressure Control module allows the simulation of three different control strategies of the RRTC PCVs in order to select the best one for the specific WDN and accounting for the actual pressure/flow measurements available at the device.

Keywords: Water Distribution Systems; Models; Leakages; Real Time Control; Pressure Reduction Valves.

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1. Introduction

The classic pressure control valves (PCVs) are mechanical/hydraulic devices which maintain a pressure target value downstream or upstream the valve, namely pressure reduction or sustain valves. Modelling this behavior in water distribution networks (WDNs) requires the setting of a target pressure at the downstream or upstream node, with respect to flow direction of the pipe where the PCV is installed. The main drawback of the classic PCVs is that they require to set a target pressure to vary over time with the hydraulic system behavior and, in particular, with the pattern of the delivered water. For example, a PCV controlling the upstream network requires higher target pressure when the delivered water flow increases because the network head losses increases with flow. This circumstance requires to set different pressure values depending on the predicted delivered water; for this reason two set pressures are generally adopted for night and daily functioning. However, the valve operation is neither optimal nor reliable because the selection of the target pressure is based on a fixed water demand which is not constant at all varying the hydraulic behavior of the WDN during the day, the week and the year.

In order to overcome this drawback technical literature [1,2,3,4,5,6] proposed PCVs to be remotely controlled in real time by pressure values set in strategic points – critical nodes – of the hydraulic system. The critical node is the "worst" node, hydraulically speaking, i.e. the first node where the pressure falls below the value desired to provide a proper water supply service. The position of the critical node does not generally vary over time because it depends on the local elevation, building height and on the required residual pressure for supplying sufficient water [7]. In this way, thanks to the current technological possibilities to easily transfer packages of pressure data, it is possible to control the valve state in order to maintain a target pressure at the remote critical node.

It is worth to note that the variation of the pressure at the control node integrates the hydraulic system behavior with respect to water requests, e.g. a decrease of water request increases the pressure and vice versa. For this reason, maintaining the target pressure at the critical nodes requires the adjustment of the opening degree (i.e. the head loss generated by the PCV) in order to enable a pressure change at the downstream node of the valve depending on WDN behavior.

Therefore, RRTC of PCVs is effective in order to optimize pressure management of WDNs, although the critical node needs to be controllable, i.e. the valve should be actually fully controlled by the pressure in the critical node over time thus adjusting the hydraulic system behavior. In addition, the control of the valve needs to be performed at each time control step because the node is far from the device and the system status cannot change instantaneously as pressure measure differs from the target value at the critical node. Otherwise, an over-controlling of the PCV may ~~results~~ in a dangerous oscillation of the flow causing relevant unsteady flow processes into the network.

This paper describes the functionality of the WDNetXL [8] – Pressure Control module which allows planning RRTC of PCVs, i.e. the analysis assuming the instantaneous achieving of the target pressure, and also the simulation in their real time operation. In fact, the simulation of the actual functioning of those valves requires the selection of the proper control time step and the definition of a strategy to adjust the valve setting in order to lead the pressure at the critical node to the desired target value.

2. RRTC of Pressure Control Valves in WDNetXL

The aim of PCVs is to maintain target pressure value which is set in a node of the WDN. PCVs maintain the pressure set reducing or sustaining the pressure by means of the movement of a shutter or membrane. In turn, a PCV reducing pressure is a device which increase/reduce the internal head loss in order to reduce/increase the pressure at the control node to the target value, while a PCV sustaining pressure is a device which increase/reduce the internal head loss in order to increase/reduce the pressure at the control node to the target value. PCVs are devices that can be modelled as a local head loss,

$$\Delta H_{PCV} = \frac{\xi}{2g} v^2 = \frac{\xi}{2gA^2} Q^2 = K_{ml} Q^2 \tag{1}$$

Where ΔH_{PCV} is PCV head loss; ξ is a variable head loss coefficient of the PCV; K_{ml} is the resistance of the PCV; V is the pipe velocity; Q is the pipe flow; A is the cross-section area of the pipe and; g is the gravitational acceleration.

Therefore, the displacement of the internal mobile device (membrane or shutter) modifies PCVs resistance (or head loss coefficient) and downstream pressure.

For electrically controllable valves like plunger or needle valves, manufacturers provide mathematical curves that allow calculating the head loss coefficient ξ associated to valve opening degree α. Irrespectively of the valve size, such curves can be properly interpolated by power laws like [4]:

$$\xi(\alpha) = 10^{-k_1 \log(\alpha) + k_2} \tag{2}$$

The shutter opening degree α is the ratio between the valve opening (shutter position) and the total shutter stroke (valve fully closed means $\alpha = 0$ and valve fully open means $\alpha = 1$). Fig. 1 shows the curve $\xi = \xi(\alpha)$ for a needle valve without anti-cavitation basket by PAM-St Gobain and expressed through Eq. (2) using k_1=2.8 and k_2=1.5.

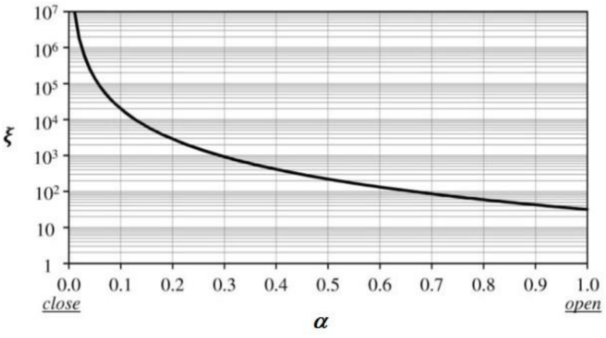


Fig. 1. Head loss coefficient ξ associated to opening degree α using k_1=2.8 e k_2=1.5 in Eq. (2).

The PCVs can have three states: (i) active when the head loss is set and the target pressure value is maintained; (ii) fully closed when the valve closes because the pressure cannot be further reduced/increased to reach the target value; (iii) fully opened when the valve opens because the pressure cannot be further increased/reduced to reach the target value. There is also a fourth status related to the inversion of flow. In fact, such a devices are usually equipped with a non-return valve, i.e. they are directional devices [8].

As said in the introduction section, the drawback of the classic PCVs resides into the fact that they require to set a target pressure which is actually varying over time with the hydraulic system behavior and, in particular, the delivered water. PCVs, remotely controlled in real time by target pressure values which are set at critical nodes of the hydraulic system, have been recently proposed in technical literature [3, 4].

Electrically controlled PCVs, can be adjusted according to remotely acquired target pressure values which are set at critical nodes of the hydraulic system [3, 4]. Data Transfer data from the remote node to the PCV allow to control the valve state by adjusting the valve resistance K_{ml} of Eq. (1)

Therefore, Remote Real Time Control (RRTC) of PCVs is effective in order to optimize pressure management of the hydraulic system for background leakage reduction, but the critical node needs to be controllable, i.e. the valve should be actually fully controlled by the pressure in the critical node over time thus adjusting the hydraulic system behavior. In addition, the control of the valve needs to be performed at each time control step (Tc) since the node is far from the device and the system status cannot change instantaneously. In the opposite case (i.e., abrupt change of the shutter), the PCV would be over-controlled resulting in a dangerous oscillation of the flow which may determine relevant unsteady flow processes into the network.

Methods to control the valve in the field make normally use of PLC based controllers (Programmable Logic Controllers). Based on acquired pressure measurements at the set node, such controllers estimate the deviation (ΔH_{set}) with respect to the desired pressure and calculate the needed valve adjustment (i.e. in terms of resistance or shutter opening) to lead the system to the target pressure value.

In any case, the RRTC PCVs requires a strategy to tune the variable resistance, K_{ml} during Tc i.e. to adjust the shutter degree α (see Fig. 1) using a control function of ΔH_{set}.

It may be argued that three main strategies can be adopted based on the three control variables of the unit process function: (i) the valve resistance, K_{ml}; (ii) the valve head loss, ΔH_{PCV} and; (iii) the shutter degree, α. Hence,

$$\begin{aligned} & K_{ml}\left(t,t+Tc\right)=-\Delta H_{set}\left(t-Tc,t\right)/Q_{PCV}^{2}\left(t-Tc,t\right)+K_{ml}\left(t\right) && \text{valve resistance control} \\ & \Delta H_{PCV}\left(t,t+Tc\right)=\Delta H_{set}\left(t-Tc,t\right)+\Delta H_{PCV}\left(t\right) && \text{valve head loss control} \\ & \alpha\left(t,t+Tc\right)=-k_{c}\Delta H_{set}\left(t-Tc,t\right)+\alpha\left(t\right) && \text{valve shutter degree control} \end{aligned} \tag{3}$$

The first two control strategies are related to hydraulic variables (K_{ml} or ΔH_{PCV}), while the third is related to the mechanical variable (α) modifying the hydraulic resistance of the valve.

In the case of valve resistance (K_{ml}) control the variation of resistance in Tc (ΔK_{ml}) is computed by means of the difference between the target and achieved pressure value at set node (ΔH_{set}) and a flow measurement at valve (Q_{PCV}) which allows to transform ΔH_{set} in a resistance value. Then, the argument (t – Tc, t) of ΔH_{set} and Q_{PCV} represents the value of the pressure difference and flow readings, e.g. the average value from t – Tc to t, and the argument (t, t + Tc) of the control variables K_{ml} indicates that the PCV status is changed during Tc from t to t + Tc starting from the initial values in $K_{ml}(t)$.

The valve head loss control (ΔH_{PCV}) is based on the idea of adjusting from t to t + Tc the valve head loss based on readings of ΔH_{set} from t – Tc to t starting from $\Delta H_{PCV}(t)$. This control function requires the measurement of the valve head loss by means of a differential pressure measurement across the PCV.

The third case relates to the direct prediction of the shutter degree α based on ΔH_{set}. The approach requires the calibration of k_c that is the proportional gain of the control function in order to transform the degree into pressure variation at the control nodes. Clearly, k_c needs to be calibrated [3] and it is not dimensionless.

According to the process, major companies producing PCVs agree that the needle valves are likely the most appropriate ones for fine pressure regulation in WDNs, being conceived to avoid cavitation, fast mechanical wearing and/or need of periodical recalibration. In fact, these valves normally have proper shutter profile that helps minimizing flow turbulence. However, it is worth to note that these conditions may be assumed under steady flow conditions, while few knowledge exists on valves operating under unsteady flow conditions generated by frequent shutter opening-closing cycles.

Finally, the adjustment of valve shutter degree is achieved according to the mechanical constraint related to the maximum velocity of the shutter, $v_{shutter}$. Accounting for maximum velocity is very important when modelling the actual behavior of the RRTC PCVs. In fact, this constraint avoids unsteady flow instabilities thus limiting the adjustment of the valve when sudden variations of pressure at the critical node occur~~s~~. The maximum valve shutter degree is then given by the product of Tc and $v_{shutter}$.

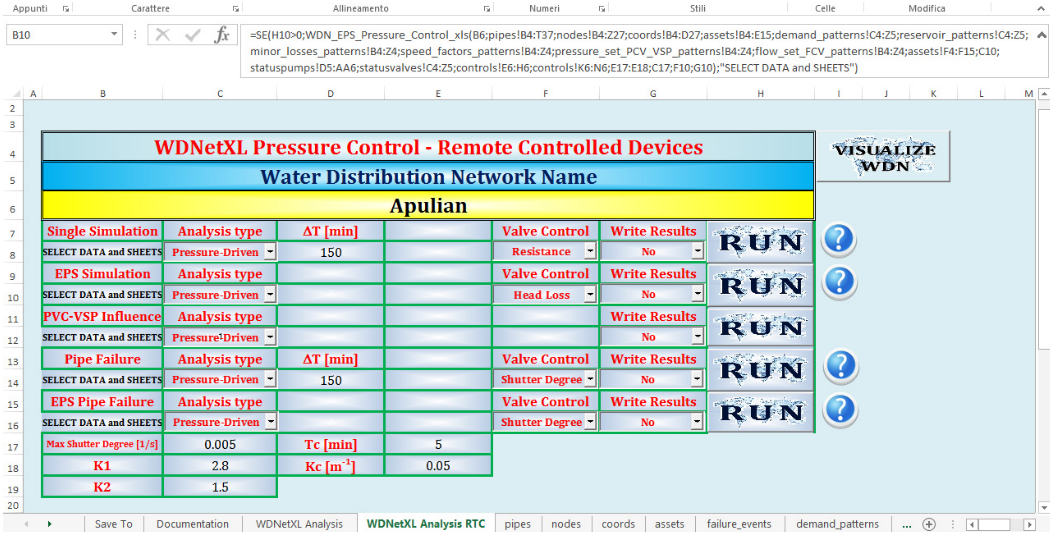
3. RRTC modelling using WDNetXL Pressure Control module

The novel WDNetXL module named WDNetXL - Pressure Control contains functions to perform the standard hydraulic and topological analyses of WDNetXL [8] considering pressure-driven simulation, background leakages [10] and different components of demand [7] and failure event, i.e. hydraulic analysis considering valve shutdowns in order to isolate a portion of the network for planned and unplanned works. The standard analysis functions allow to model any device and in particular the RRTC PCVs and variable speed pumps (VSPs). However, the analysis is conceived as planning analysis, i.e. it is assumed that the target pressure can be reached instantaneously by controlling the device status somehow. This assumption can be accepted when the control node is just upstream (only for PCVs) or downstream the devices, with respect to water flow, because the adjustment of the pressure is local and immediate since it produces a variation of the network status which does not generally influence the target pressure reaching. On the contrary, the assumption of RRTC devices by itself neglects the fact that the pressure at the remote node (critical node) is influenced by the network behaviour which changes because of the device adjustment and for natural/statistical reasons (e.g. costumer water requests).

Therefore, the planning analysis of the RRTC devices is useful in order to plan their location into the network, the position of the critical node, the mutual interference, etc. *Vice versa*, the operational functioning of those devices needs to be analyzed considering the actual functioning over *Tc*, the implemented control function, the specific valve curve, the shutter maximum degree, etc.

For this reason, WDNetXL - Pressure Control implements the same functions of the planning analysis but considering the actual functioning over time for the RRTC devices. This means that the analysis is performed at each control step *Tc* assuming a linear variation of the demand pattern (since time steps used for defining demand patterns – e.g. 1 hour – might include multiple time steps for RRTC control – *Tc* of few minutes) and considering as RRTC devices only the PCVs and VSPs which are controlled by nodes that are none of the two ending nodes of the pipe where the device is installed.

Fig. 2 reports the user interface of the template in WDNetXL - Pressure Control module allowing to set and run the RRTC device modelling functions. It is worth to note that those functions requires to define *Tc*, possibly the values k_1 and k_2 of Eq. (2), the selection of the control strategy and the gain factor k_c (working only when the shutter degree strategy is used as in Eq. (3)).



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=SE(H10>0;WDN_EPS_Pressure_Control_xls(B6;pipes!B4:T37;nodes!B4:Z27;coords!B4:D27;assets!B4:E15;demand_patterns!C4:Z5;reservoir_patterns!C4:Z5;
minor_losses_patterns!B4:Z4;speed_factors_patterns!B4:Z4;pressure_set_PCV_VSP_patterns!B4:Z4;flow_set_FCV_patterns!B4:Z4;assets!F4:F15;C10;
statuspumps!D5:AA6;statusvalves!C4:Z5;controls!E6:H6;controls!K6:N6;E17:E18;C17;F10;G10);"SELECT DATA and SHEETS")
```

WDNetXL Pressure Control - Remote Controlled Devices

Water Distribution Network Name

Apulian

Single Simulation	Analysis type	ΔT [min]		Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven	150		Resistance	No
EPS Simulation	Analysis type			Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven			Head Loss	No
PVC-VSP Influence	Analysis type				Write Results
SELECT DATA and SHEETS	Pressure-Driven				No
Pipe Failure	Analysis type	ΔT [min]		Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven	150		Shutter Degree	No
EPS Pipe Failure	Analysis type			Valve Control	Write Results
SELECT DATA and SHEETS	Pressure-Driven			Shutter Degree	No
Max Shutter Degree [1/s]	0.005	Tc [min]	5		
K1	2.8	Kc [m^{-1}]	0.05		
K2	1.5				

Fig. 2. Template in WDNetXL for RRTC device analysis.

The block of functions of WDNetXL - Pressure Control for RRTC device analysis (see Fig. 2) is composed by four analysis functions allowing steady state simulation and extended period simulation under normal and pipe failure conditions (i.e. considering the shutdowns of relevant gate valves) as well as the standard hydraulic analysis.

4. Planning Analysis vs. RRTC Devices Operative Functioning Analysis

We here use the Apulian network (see Giustolisi et al. [10] for further details) in order to show planning analysis (see the previous section) versus operative functioning of RRTC devices according to real-time transfer of pressure measures to Programmable Logic Controller (PLC) units driving the devices as described in the previous sections.

The minimum required pressure for any water supply and for a correct service of the Apulian WDN were assumed equal to 0 and 10 m, respectively, and kept constant through the network. The parameters of Germanopoulos' model [11] for background leakages were set equal to α=1.2 and β=5.03×10^{-8} for the entire network. Fig. 3 reports the network layout and the daily pattern of the customer demand factors.

In order to control pressure over time, the installation of a PCV on pipes P34 (designated as “PV” in Fig. 3) is assumed. The PCV is controlled by means of pressure reading in the critical node N10 [5]. It is treated as RRTC devices being not controlled by node N1 just downstream the device as it is the classic way of modelling pressure reduction valves. Figure 4 reports the pressure in node N10 using the planning analysis. It is worth to note that the PCV is active from hour 1 to 5 and from hour 20 to 24 and the pressure is maintained to the target value assumed equal to 15 m, while during different time periods the valve is fully open because the pressure in N10 is lower than target pressure.

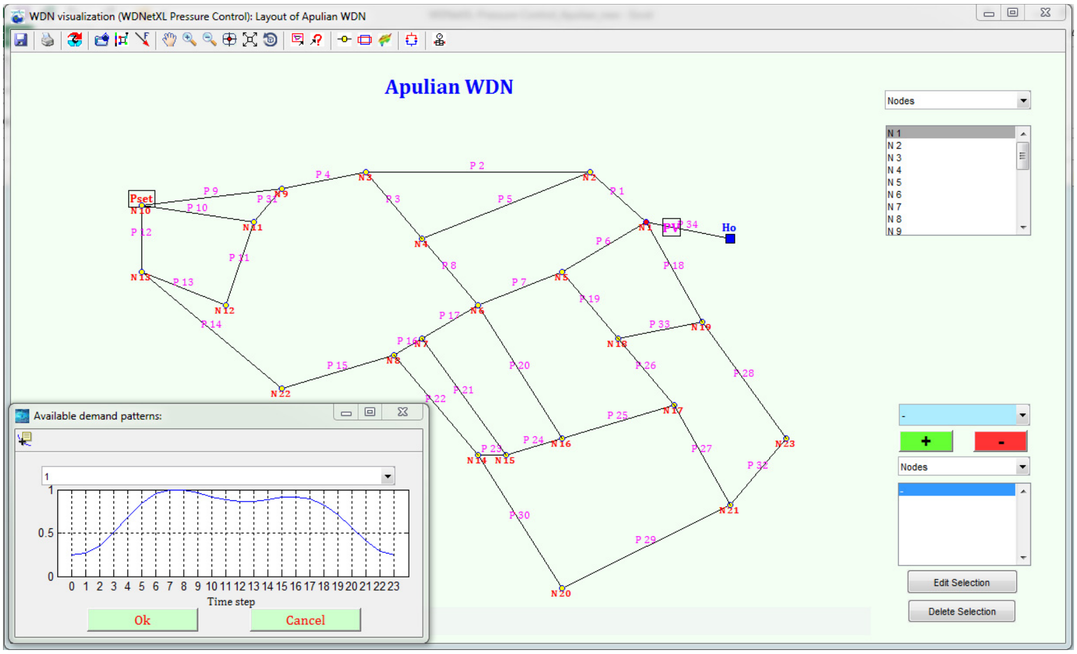

Fig. 3. Network layout and demand time pattern.

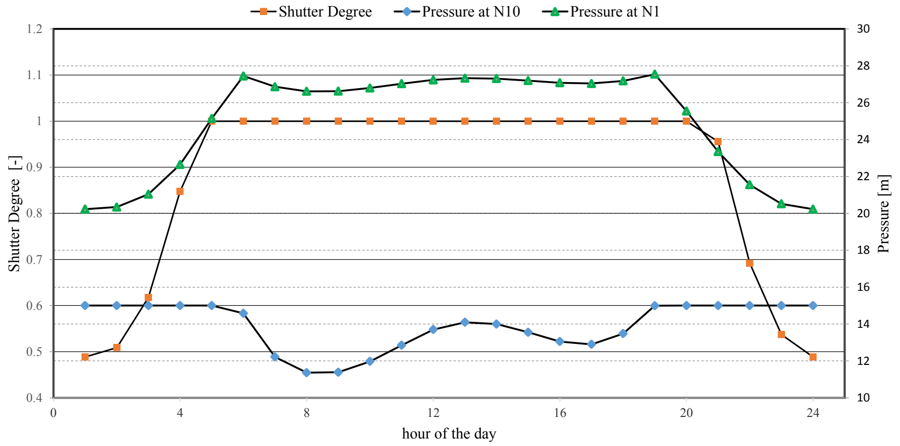

Fig. 4. Pressure at nodes N10 and N1 and shutter degrees of planning analysis.

In fact, Fig. 4 shows the shutter degree of the installed PCV (pipe P34) to be equal to unit from hour 6 to 19 (the shutter degrees at hours 5 and 20 are very close to unit). The same figure reports the pressure values at node N1;

those pressure values demonstrates that, in order to obtain the target value equal to 15 m at node N10 a classic PCV controlled by means of a downstream node (N1) would requires to modulate over time the target pressure in that node form 20 to 25 m in the specific case. Moreover, the classic/local strategy (i.e. without accounting for RRTC) asks to select the daily window without control, from hour 6 to 19 in the specific case. Therefore, the classic control requires some decision about a single target pressure that is not optimal or the use of a modulating target pressure that is not reliable with respect to water demand uncertainty. RRTC devices, instead, show to be much more reliable form the hydraulic standpoint because pressure measurements at the critical node integrate the hydraulic behavior of the network making flexible the control with respect to demand request uncertainty.

Figures 5, 6 and 7 report the results of the simulations of the RRTC device installed on pipe P34 and controlled by readings at the node N10 using the control variable of Eqs. (3): (i) resistance; (ii) head loss and; (iii) shutter degree. In the case of variable shutter degree two values of k_c were tested {0.05, 0.01}. They correspond to a different response of the device control to pressure variations at node N10 with respect to the target value (15 m).

In all cases the velocity of the shutter ($v_{shutter}$) was set to 0.0005 s^{-1} and the time step of the control (*Tc*) to 5 min, therefore the maximum shutter degree in *Tc* is 0.15, and the initial status of the valve was assumed fully open.

As already discussed, Figures 5, 6 and 7 show that the use of the shutter degree as control variable poses the need of calibrating [4] k_c because a quicker response of the device ($k_c = 0.05$ m^{-1}) is effective when the pressure at N10 is close to 15 m. On the contrary, the control results not effective in the first hours of the day and oscillations of the pressure (and then of the shutter displacements and resistance) occur. In fact, the initialization of the device as fully open means to start from pressure equal to 26 m at node N10 which is far from the target value (15 m). For this reason, the shutter initially moves during *Tc* of 0.15 degree, as in Figures 6 and 7, and oscillates for the first hours before reaching the value of the pressure close to the target one as in Figure 5.

The need of a calibration for k_c is confirmed by the assumption of $k_c = 0.01$ m^{-1}, i.e. a slower device response of the device. However, $k_c = 0.01$ m^{-1} seems to be not optimal to maintain the pressure to 15 m as the delivered water changes from hour 2 to 5. Therefore, a reliable calibration of k_c should be performed considering the maximum variation of the pressure generated by the variable network behavior over time. The need for a reliable calibration, however, dominates with respect to the optimality of the control in term of response velocity of the device.

Figures 5, 6 and 7 show that the use of the device resistance as control variable is much more effective with respect to shutter degree although it requires the measurement of the flow rate. In fact, the first of Eqs. (3) allows to calculate $K_{ml}(t, t + Tc)$ which correspond to a new shutter degree to be reached (see Fig. 1) starting from $K_{ml}(t)$ and considering the maximum degree in *Tc*. The effectiveness of the resistance as control variable is explained by the fact that it can be correlated to hydraulic behavior of the WDN and to a variable proportional gain depending on $Q_{PCV}(t - Tc, t)$ as from the rewriting of the first of Eqs. (3),

$$\begin{aligned} & K_{ml}\left(t,t+Tc\right) = -\frac{1}{Q_{PCV}^{2}\left(t-Tc,t\right)}\Delta H_{set}\left(t-Tc,t\right) + K_{ml}\left(t\right) \\ & \overset{k_c = Q_{PCV}^{-2}\left(t-Tc,t\right)}{\Leftrightarrow} \quad K_{ml}\left(t,t+Tc\right) = -k_c \Delta H_{set}\left(t-Tc,t\right) + K_{ml}\left(t\right) \end{aligned} \tag{4}$$

Consequently, the state of the device, as an optimal and reliable response to the network behavior, changes over time because the flow measurement from $t - Tc$ to t are a good indicator of the network status.

Furthermore, Figures 5, 6 and 7 show that the head loss at the device is slightly more effective control variable with respect to resistance. In fact, the second of Eqs. (3) transforms a pressure variation with respect to the target value at the node N10 in a variation of the head loss at the device. This approach requires a strategy to move the RRTC device in order to increase or decrease the valve head loss in *Tc* at the target value computed by means of the second of Eqs. (3) and for this reason the differential pressure measurement is required.

It is possible to conclude that WDNetXL allows the simulation of different control strategies of the RRTC PCVs in order to select the best one for the specific WDN and accounting for the actual pressure/flow measurements available at the device. In any case, the reliability and optimality of the control using the valve resistance or head loss as control variable would suggest planning the relevant cost of measurements.

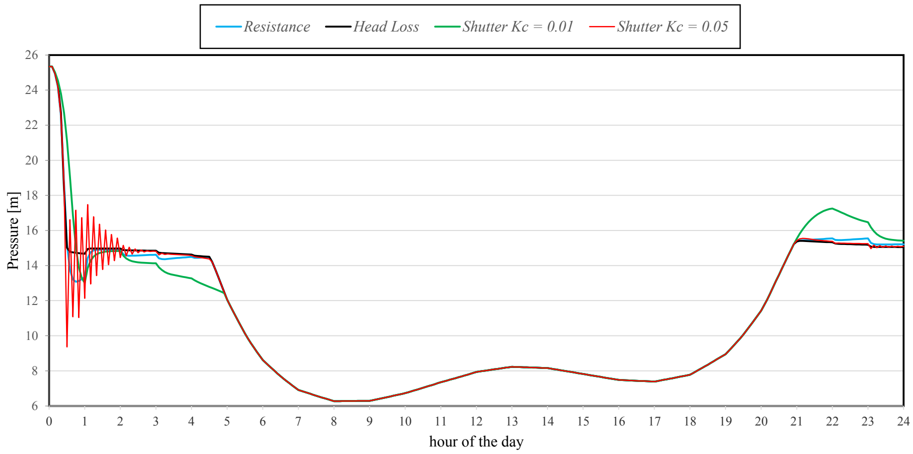

Fig. 5. Pressure values at N10 using control strategies of Eq. (3) and two values of k_c. The target pressure is 15 m.

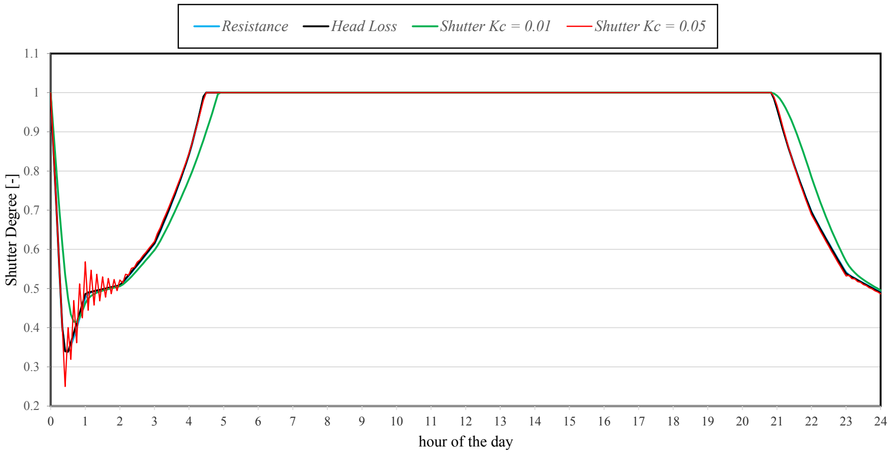

Fig. 6. Shutter degrees using control strategies of Eq. (3) and two values of k_c.

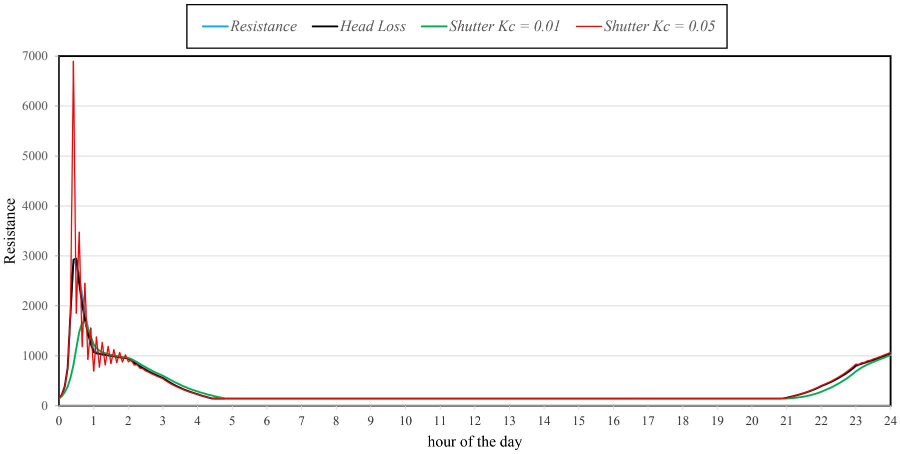

Fig. 7. PVC resistance using control strategies of Eq. (3) and two values of k_c.

5. Concluding remarks

The work presents the WDNetXL - Pressure Control module, which is a collection of MS-Excel add-ins for planning and operative functioning analyses of remote real time control (RRTC) of pressure device in water distribution networks (WDNs). In fact, the communication technologies nowadays allow the real-time transfer of pressure readings from remote/critical nodes to PLC units driving the devices. Three strategies, which correspond to different unit process transfer functions, have been presented and discussed for RRTC pressure device control. Two strategies are novel and do not require the calibration of the proportional gain parameter although they require a differential pressure or a flow measurement at the pressure reduction valve. It is worth to note that the user-friendly environment WDNetXL - Pressure Control allows just in time research transfer to students and technicians, sometimes anticipating research publications, and embeds the recent advances in hydraulic analyses already implemented in WDNetXL.

Acknowledgements

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