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Pressure control for WDS management. A case study

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Abstract

The paper presents the analysis of the water distribution system of the town of Chiaravalle, in Central Italy. A hydraulic model of the network is implemented and calibrated to improve the system management. Besides the possibility of reducing the service pressure by inserting some pressure reducing valves, the economic convenience of coupling the valves with the pumps as turbines to covert energy dissipation in energy production is investigated. The determination of the number, location, and setting of such valves and machines are described together with the effects of the pressure control.

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Keywords: water distribution system; pressure reducing valve; pump as turbine; energy recovery

1. Introduction

In the last years many water utilities have started up a pressure control policy for the management of the water distribution system (WDS) by the installation of pressure reducing valves (PRVs). Indeed, the reduction of excess pressure in the network gives the reduction of leaks and pipe bursts and limits the water resource loss. A further challenge for the WDS managers is represented by the energy saving. However, although the number of the cases where PRVs are installed is increasing, only few attempts were accomplished in order to convert energy dissipation in energy production. The more common application consists of inserting turbines in the transmission pipelines, characterized by an available hydraulic power significant and quite constant. Conversely, the large variability in flow rate and head drop of the WDS limits the economical convenience of dissipation conversion by means of this kind of machines. The cheapest and most sustainable solution for energy production seem to be PAT (pump as turbine) systems, even if no standard design criteria are available. This paper presents some results of an widespread analysis

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of the WDS of the town of Chiaravalle, in the central part of Italy, aimed to improve the system management. The hydraulic model of the network has been implemented with EPANET [1] and calibrated after two successive campaigns of pressure measurements. The numerical simulations allowed us to analyse the behaviour of the network under different operating conditions and to verify the possibility of reducing the service pressure by inserting some PRVs. The determination of the number, location, and setting of such valves are described together with the effects of the pressure control. On the basis of the these results, the possibility of coupling the PRVs with the PATs is investigated in the last part of the paper. Different scenarios involving PATs are analysed in order to identify the most suitable solution in terms of energy power production without compromising the hydraulic performance of the network in terms of service delivery.

2. Pressure control for WDS management

2.1. Pressure reducing valves PRVs

Several studies are concerned with management of WDS service pressure. During recent years, being optimization problems with objective functions and nonlinear constraints, these issues are analyzed by optimization techniques based on genetic algorithm. In the literature several works analyze the problem of pressure reducing valve regulation by using these techniques (e.g. [2]).

An alternative solution are real time control techniques and the adoption of controllers that regulate valves on the basis of the informations collected in the network. In this way the valves controlled in real time adapt themselves in automatic manner to the operative conditions of the network related to water demand variations [3]. Current technical solutions are available for pressure control through PRVs: e.g. PRVs with motorized pilot or local controller or time set local controlled PRVs and PRV with mechanical/hydraulic controller. The choice of the valve positions is a fundamental aspect to obtain a significant reduction of the losses and of the pipe breaking number. The search of the optimal positions can be based on a heuristic procedure [4] or on a genetic algorithm [5].

2.2. Pumps as turbine PATs

Towards a virtuous energetic policy, few attempts are carried out to convert energy dissipation in energy production [6,7]. The use of turbines in the WDS requires a careful preliminary analysis to ensure many aspects such as optimal choice of the equipment, exactness of pressure values of the network, control of water quality and water-hammer effects on pipes resistance [8]. It is possible to install two kinds of machine: reaction turbine or pump as turbine (PAT). In the first case the turbine is optimized on the base of the specific installation but its construction could be expensive; in the other case there is a wide choice between commercial products and the solution is to find the equipment with the best efficiency.

Since pump manufacturers do not normally provide the characteristic curves of their pumps working as turbines, for selecting the proper machine it is necessary establish a correlation between the performances of direct (pump) and reverse (turbine) modes. The method for obtain both characteristic and efficiency curves can be divided in three groups: experimentally, by computational fluid dynamics (CFD) and by any one-dimensional method [8]. The first choice is the most reliable, but a large number of experiments is necessary for the whole range of flow conditions and generator rotation speed [6].

3. The PAT selection and the energy production

To identify the pumps satisfying the turbine operating conditions of both head and flow, Derakhshan and Nourbakhsh [9] tested several low specific-speed centrifugal pumps as turbines. Using experimental data, they derived some relations to calculate the best efficiency point BEP of a pump working as a turbine, from the BEP of the pump mode.

After computing the BEP of PAT, the complete characteristic curves of centrifugal pumps as turbines can be obtained. Dimensionless head and power curves of a PAT can be estimated using second and third order polynomials, respectively:

$$\frac{H_t}{H_{tb}} = 1.0283 \left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468 \left(\frac{Q_t}{Q_{tb}}\right) + 0.531, \tag{1}$$

$$\frac{P_t}{P_{tb}} = -0.3092 \left(\frac{Q_t}{Q_{tb}}\right)^3 + 2.1472 \left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865 \left(\frac{Q_t}{Q_{tb}}\right) + 0.0452, \tag{2}$$

where H, P and Q, are head, power and flow rate, while subscripts p, t and b are related to pump, turbine and BEP. Efficiency curve can be obtained straightforward for each point from the power.

Besides the turbine mode performance of a pump, in practical applications a procedure is required to select the proper PAT. The technique proposed by [9] uses the rated point, that is the operating point of the machine, which depends on the site conditions and usually not exactly coincides with design point or the BEP of the machine. Further details about this method can be found in [9].

Finally, the selection of the most suitable machine and of operating conditions should be carried out on the basis of technical considerations on the PAT efficiency and a preliminary economic analysis. The method proposed by De Marchis and Freni [7] can be adopted for estimating the economic advantages of the PAT installation in WDS. After computing the power of the PAT at the BEP, the Energy Generation Equipment (*EGE*) cost can be estimated considering 2000 euro/kW for power installed

$$EGE = P \cdot 2000\ \text{€/kW}. \tag{3}$$

To compute the capital payback period (*CPP*), it is necessary estimate the overall costs given by *EGE*, Civil Works (*CW)* and Maintenance Costs *(MC)*. The cost of the civil works is assumed to be the 30% of *EGE*

$$CW = 0.30 \cdot EGE, \tag{4}$$

and the maintenance cost is evaluated as the 15% of the sum of the two previous entries as

$$MC = 0.15 \cdot (EGE + CW). \tag{5}$$

The Annual Financial saving (*AF*) is calculated by considering a produced energy cost equal to 0.22 €/kWh, as it is the average value for the renewable energy produced in Italy

$$AF = 0.22 \cdot AYEP - MC, \tag{6}$$

where $AYEP$ is the Average Yearly Energy Production. The Capital Payback Period is given by

$$CPP = (EGE + CW) / AF. \tag{7}$$

4. The case study

The proposed analysis has been applied on the WDS of the town of Chiaravalle, in the central part of Italy. The system serves about 15000 inhabitants and it is a fully gravitational network supplied by a main reservoir. The WDS is characterized by high service pressures in some areas of the town. The hydraulic model of the network has been implemented with EPANET. Additional details on both the network and the hydraulic model can be found in Darvini and Soldini [10].

The model has been calibrated after two campaigns of pressure measurements. A first survey was carried out during the period from 13 November to 28 November 2013 and it is described in detail in Darvini and Soldini [10]. Pressures were measured by six manometers installed throughout the distribution system. The collection of measurements was complicated by a malfunction of the pressure sensors and an anomalous behaviour of the daily mean flow provided by the remote control of the reservoir during the entire measurement period. For these reasons, an ulterior campaign has been performed in the period 9-20 April 2015. To overcome some difficulties arisen during the previous attempts of model calibration, two locations of the six monitored nodes have been changed. In particular, one of the pressure sensors has been placed at node 1, along the conduct coming from the reservoir to monitoring the behaviour of the pressure at the entrance of the network. This measure allowed to reduce significantly the overall error in the calibration procedure.

A malfunction of the remote control at the reservoir has led to lack of recorded data for longer or shorter time periods and this inconvenience has limited the choice of the days for the model calibration and successive validation. Since the data series of the flow recorded are the most complete in comparison with other working days, for the model calibration have been chosen measurements collected on April, 10.

The spatial distribution of demand has been calculated on the basis of the annual water consumption measured at each users of Chiaravalle town and grouped on the basis of the house number of each street. Analysing the data over the period January 2013 – December 2013, the daily mean value of the total flow rate of the network is equal to 24.965 l/s. This value is different from the average flow entering the network and measured at the reservoir in the same period of 36.875 l/s. The gap represents about the 32% of the average flow entering the network, but the flow data measured at the reservoir during the year showed an anomalous behaviour from 17 August to 10 December characterized by an increase of the flow that in the night hours is about of 10 l/s. In the period of measurements the average flow entering the network is 34.328 l/s and values of nodal demands have been corrected by multiplying initial values of demand with the ratio between the average outlet of the reservoir and the daily mean flow requested by the network.

For calibrating the network model the approach proposed by Greco and Del Giudice [11] is adopted. The calibration algorithm considers as decision variables pipe roughness ε. The objective of this method is to minimize the sum of the squares of the differences between the unknown variable ε and the initially assumed parameter ε*, under the constraint that measured and computed response of the model differ by less than a specific tolerance. Links have been grouped on the basis of material: polyethylene, high density polyethylene, asbestos cement, cast iron and steel; both initial and calibrated values of roughness are described in Table 1. As regard the user consumption, the mean demand was taken into account in the calibration procedure. The calibration was performed assuming that absolute roughness was greater than 0.001 mm and lower than 15 mm.

The absolute value of difference between measured and calculated values of pressures at six sensors after calibration is reported in Table 2. The correlation plot between measured and calculated pressure values obtained during the validation phase at the monitoring points is reported in Fig. 1. Results show that sensor at node i6 is the best calibrated while node i13 is the worst.

Table 1. Initial and calibrated values of pipe roughness used in the hydraulic model.

	ε_{PE} (mm)	ε_{PEHD} (mm)	ε_{AC} (mm)	ε_{CI} (mm)	ε_{S} (mm)
Initial value	0.02	0.002	0.16	1.5	0.15
Calibrated value	0.001	0.001	0.001	0.233	0.044

Table 2. Absolute error (AE) between measured and computed pressures at six sensor nodes.

Node	1	i6	i13	156	i17	236
Pressure AE (*m*)	0.03	0.42	3.20	0.19	1.55	0.19

5. The WDS management by PRVs

The results of WDS simulation confirm the presence of high pressures in a large area of the town. The nodes in the northern part of the area are characterized by a pressure variation from a minimum of 5.2 MPa to a maximum of 7.7 MPa with the mean value equal to 6.9 MPa, while in the southern area there are pressures in the interval

(4.1÷6.4) MPa and the average pressure is of 5.5 MPa. Fig. 2a shows the modelled pressure distribution in correspondence of the minimum nodal demand. It is evident that the entirety of WDS has a pressure nodal greater than the maximum level fixed by the Italian Law (70 m of water column above the ground level) during the night and such a high value of pressure is not requested by the elevation of buildings in that area.

In order to improve the WDS efficiency by introducing the PRVs, different scenarios have been tested in the case study, being the minimum allowable pressure value equivalent to 35 m of water column. The first scenario is represented by the installation of nine valves to divide the distribution network into three districts (see Fig. 2b). The five valves in the lower part of the area are set to an operational pressure of 45 m while the setting pressure of the others is of 37 m. The results of the modelled scenario, shown in Fig. 2b, achieve the main task of reducing the pressure to the minimum value both in the northern and southern districts. Moreover Fig. 3a shows the pressure variation over the entire day in three reference nodes of the network: nodes 8, 117 and 243 that belong to each district (North, Central and South) and that represent the nodes whose elevation is the highest, the mean and the lowest respectively.

Results plotted in Fig. 3a show an optimal regulation of pressure in both northern and southern district. The average values of pressure are 4.2 MPa at node 8 and 3.8 MPa at node 243 respectively and the oscillation between maximum and minimum is of 0.8 m at node 8 and of 2.0 m at node 24. On the contrary, the central part of the network has a large pressure variation over the entire day being the pressure variable in the interval (50÷71) m, as represented in Fig. 3a for node 117. This is a consequence of the direct connection between the reservoir and the central district.

The second scenario represents the easiest solution for pressure reduction and consists of the installation of just one PRV in the pipe 69 (see Fig. 2c) whose setting is of 42.5 m. In this case, the central part of the WDS has a more stable pressure distribution with an average value of 45.4 and generally, the large part of the nodes has a pressure smaller than 50m. Moreover, the maximum pressure in the area is of 54.1 m (node 8) at 3:00 AM, while at the same time node 243 measures a pressure of 38.7 m, showing a large variation of pressure over the entire area (see Fig. 3b). Finally, the nodes in extreme northern part of the town have a pressure greater than 51 m.

The third scenario represents an optimization of previous solutions and consists of the installation of four PRVs (see Fig. 2d). One valve is installed on the main pipe (link 332) and is set to 42 m, while three PRVs have the same position and setting chosen for scenario one. Fig. 2d shows that all the nodes of the network have the pressure smaller than 50 m in correspondence of the minimum nodal demand. The results of pressure variation at the reference nodes, plotted in Fig. 3c, reveal that both in northern and central area of the town there is a very regular distribution of pressure. The pressure mean value is 44.6 m and 44.9 for nodes 8 and 117 respectively and the difference between maximum and minimum is equal to 1.6 m and 1.8 m respectively. A greater variation of pressure is shown for node 243, with a mean value of 37.1 m and difference between extremes of 3.2 m; however this result is absolutely comparable to those obtained with scenarios 1 and 2.

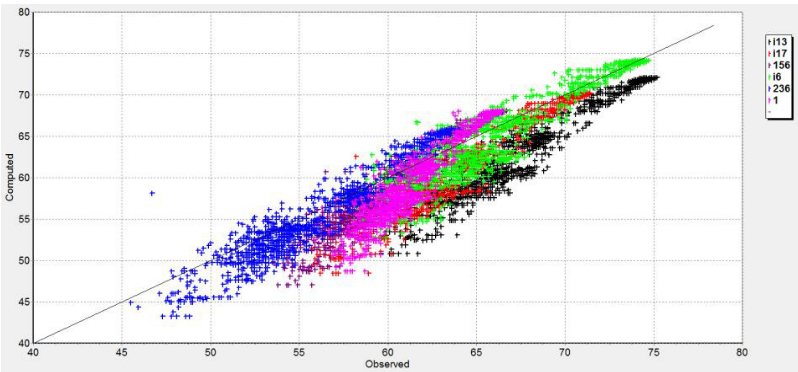

Fig. 1. Correlation plot between measured and calculated pressures obtained during the validation phase at the monitoring points.

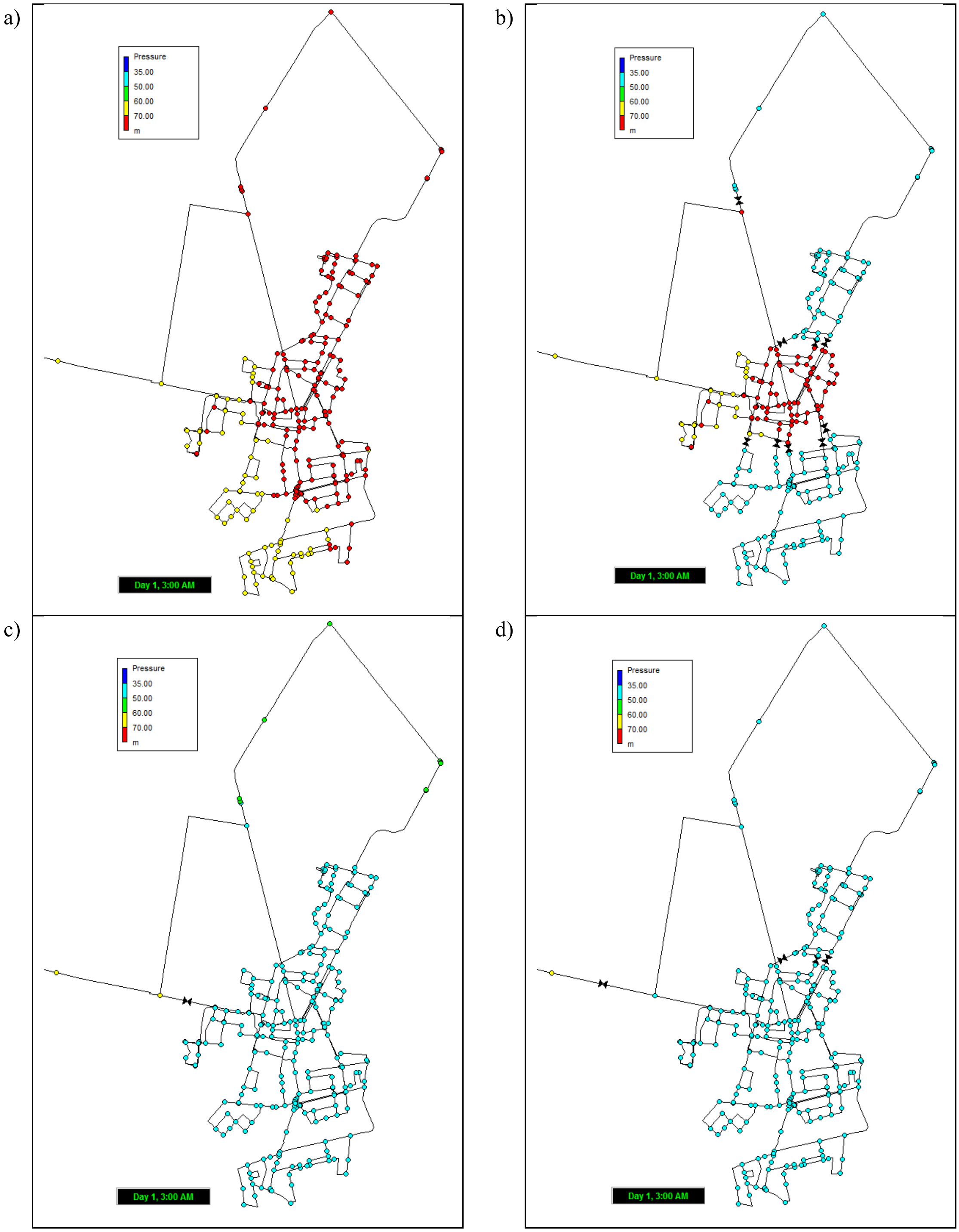

Fig. 2. Simulated pattern of maximum pressure distribution in the WDS of Chiaravalle (Italy): (a) absence of regulation; (b) regulation by PRV and creation of districts (scenario 1); c) regulation by PRV (scenario 2); d) regulation by PRV and partial creation of districts (scenario 3).

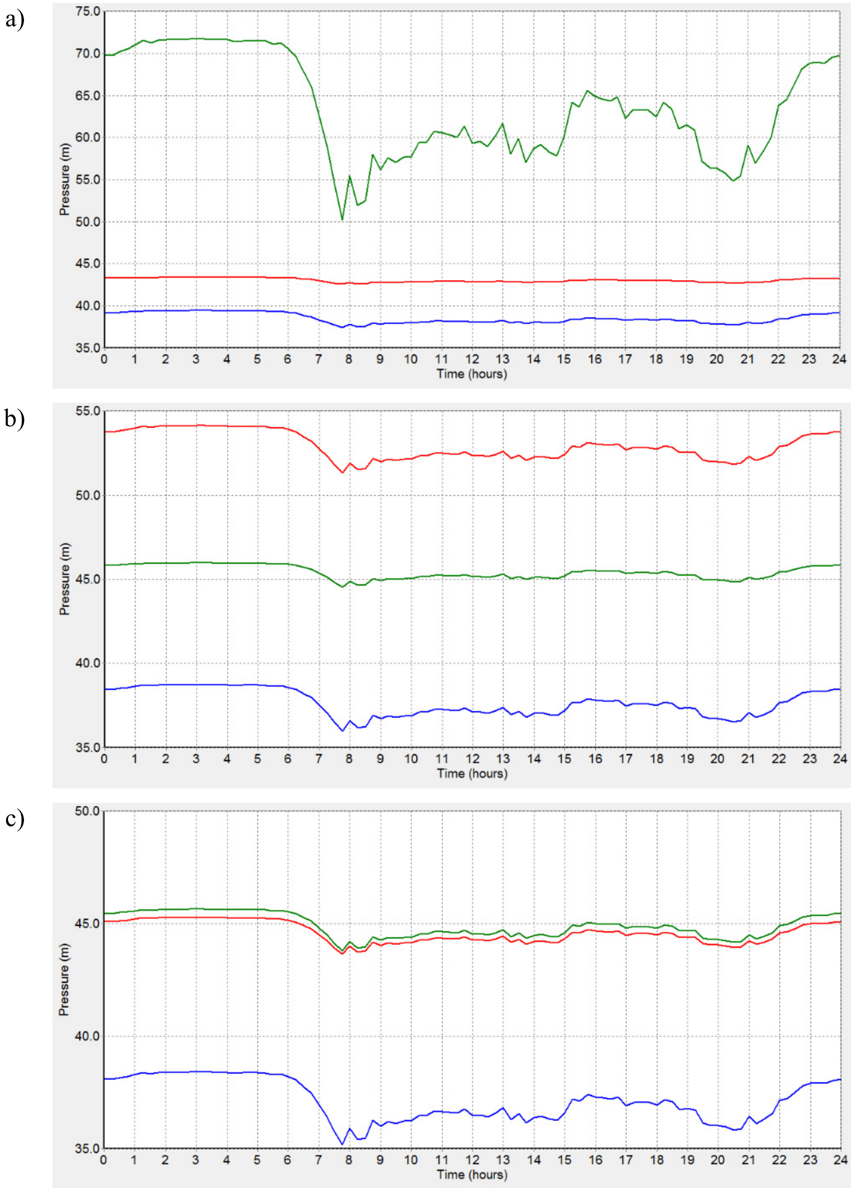

Fig. 3. Pressure variation with respect of time for node 8 (red line), 117 (green line) and 243 (blue line) by introducing PRVs: (a) scenario 1 – nine valves; (b) scenario 2 – one valves; c) scenario 3 – four valves.

6. The WDS management coupling PAT and PRVs

Installation of commercial pump working as turbine could represents an interesting opportunity to recover unused energy without compromising the network functionality.

Analysis of WDS management, obtained by installation of PRVs according to the third scenario, shows that an average energy dissipation of about 21.6 m is available at the main pipe for a possible energy recover. The main task of this approach is the selection of a pump to use for construction of characteristic curves of PAT, due to the great oscillation of flow and headloss during the day.

According to the procedure of Derakhshan and Nourbakhsh [9], the pump can be selected on the basis of its BEP, which represents the main parameter requested for the construction of PAT curves. In the time interval (9:00÷24:00) the maximum values of flow and headloss in the PRV are 47.79 l/s and 25.36 m respectively. These data are used to select a pump with its BEP close to maximum operative condition of valve and, consequently, four Caprari's pumps are analysed for energy recovery in the Chiaravalle WDS. The main technical data of selected pumps are reported in Tab. 3, while examples of pump and PAT curves are plotted in Fig. 4.

Table 3. Technical data of analyzed pumps.

ID	Type	Impeller	Q_{pb} (l/s)	H_{pb} (m)	η_{pb} (–)	Speed (1/min)	Rated Power (kW)	Frequency (Hz)
1	MEC-A1/125	A	43.6	10.5	0.767	1420	7.5	50
2	MEC-A1/125	B	41.0	9.8	0.762	1420	7.5	50
3	MEC-A1/100	A	31.0	7.78	0.789	1680	4	60
4	MEC-A1/80	A	15.8	6.19	0.739	1500	1.5	50

The head, power and efficiency curves of PAT are obtained by equations (1) and (2) and installation of PAT and PRV in parallel on link 332 is analysed. This solution is necessary to avoid both pressure values greater than 70 m or smaller than 35 m and negative values of efficiency during the functioning of the pump. In fact, when the pressure is smaller than 35 m or the efficiency of the PAT is negative, then the PAT is turned off and the PRV controls the excess of pressure. For example, the activation of a PAT n. 1 or n. 2 for all the day, determines two unwanted effects: a) the efficiency of PAT is negative during the night when the flow is very different with respect to the Q_{pb}; b) the pressure values of network are smaller than the lower limit when the headloss is maximum, i.e. when the flow is closer or greater than the Q_{pb}. Therefore, if we limit the functioning of the PAT to the interval (9:00÷24:00), the Average Yearly Energy Production (*AYEP*) obtained by PAT 1 and 2 is of about (18000÷19000) € and the Capital Payback Period (*CPP*) is of 18.8 years for PAT 1 and 15 years for PAT 2 respectively (see Tab. 4).

An alternative can be represented by the installation of PAT type MEC-A1/100, that has both smaller Q_{pb} and rated power P; consequently the efficiency is positive also during the night, when the minimum flow is about 14 l/s, as illustrated in right panel of Fig. 4. In this case, if the PAT is turned off from 7:00 AM to 9:00 AM and from 8:00 PM to 9:00 PM, the energy production is about 24000 €/year and the CPP is shorter than three years (see Tab. 4). However, the headloss of the PAT during the night is of about 4.5 m and the large part of the WDS has a pressure greater than 60 m, as illustrated in Fig. 5a. It shows that installation of PAT n. 3 and PRV in parallel does not reach an optimal control of the pressure.

Two other solutions are considered to perform a better management of Chiaravalle distribution network. The first one consists of installation of PRV in series with PAT, as shown in Fig. 5b. Taking into account the use of PAT n. 3 with the same period of turning off previously considered, the energy production is equivalent to that obtained with PAT and PRV in parallel and therefore the economic analysis gets the same positive results reported in Tab. 4 for pump MEC-A1/100A. At the same time, the PRVs regulate the pressure of the network in the interval (35÷50) m, that is a very interesting result.

Table 4. Main results of economic analysis of PAT installation.

ID	Type	Functioning (hours)	*EGE* (€)	*CW* (€)	*MC* (€)	*AYEP* (€)	*AF* (€)	*CPP* (years)
1	MEC-A1/125A	15	15000	4500	2925	17996.5	1034.2	18.8
2	MEC-A1/125B	15	15000	4500	2925	19222	1303.8	15
3	MEC-A1/100A	21	8000	2400	1560	24234.7	3771.6	2.8
4	MEC-A1/80A	7	3000	900	585	2893	51.5	75.8
5	MEC-A1/100A + MEC-A1/80A	21	11000	3300	2145	25870.4	3546.5	4

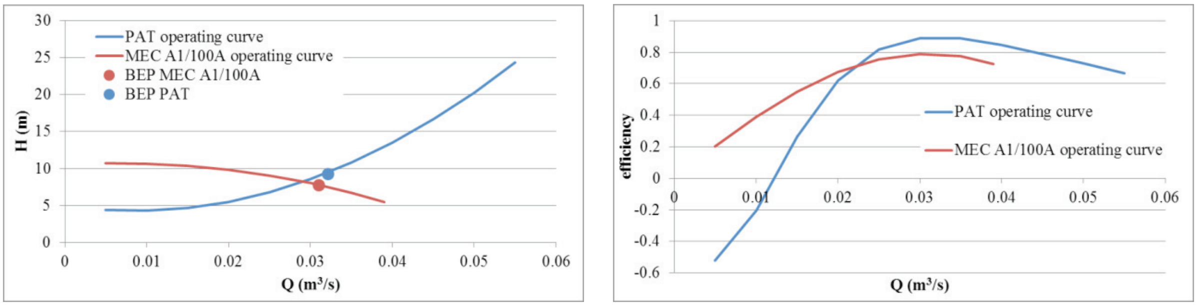

Fig. 4. Example of characteristic curves of pump and PAT type MEC-A1/100A analyzed in the WDS of Chiaravalle (Italy): head – flow curve (left); efficiency – flow curve (right).

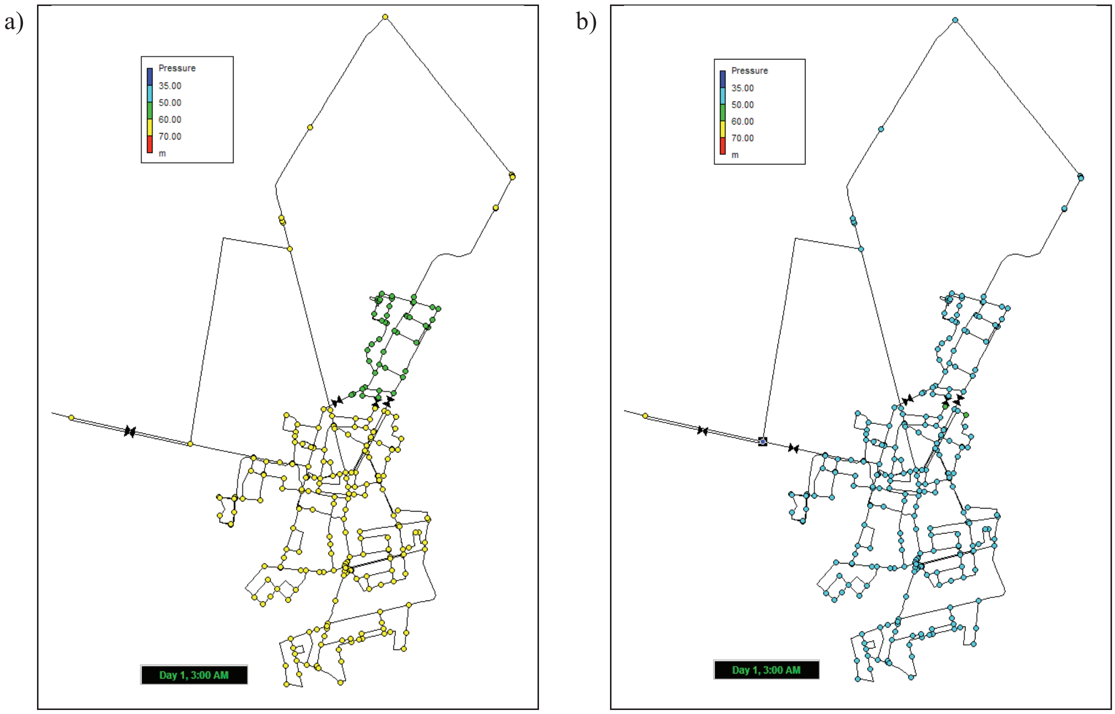

Fig. 5. Simulated pattern of maximum pressure distribution in the WDS of Chiaravalle (Italy):by introducing PAT MEC-A1/100 and PRVs: (a) PAT and PRV in parallel; (b) PAT and PRV in series.

The other solution consider to install two PATs with different periods of functioning, and a PRV in series to control the output pressure. The first PAT is MEC-A1/100A, that seems to get the best performance from the economic point of view. The second PAT, named MEC-A1/80A whose details are reported in Tab. 3, has its Q_{pb} in the interval (10÷20) l/s, in order to turn on this PAT during the night-time hours. Considering an interval of switching on from midnight to 7 AM, the PAT n. 4 has small values of both costs of investment and energy production, therefore the CPP is greater than 75 years. Also combining PAT 4, turned on from 0:0 AM to 7:00 AM, and PAT 3 turned on from 9:00 AM to 12 PM, the period of capital payback is of 4 years, in any case greater than that obtained with the installation of single PAT n. 3 (see Tab. 4).

7. Conclusions

Analysis of the pressure distribution of the WDS of Chiaravalle (Italy) revealed that the network is characterized by a maximum pressure variable in the interval (6.4÷7.7) MPa and that value is not justified by the buildings elevation of the area. Different scenarios of reducing pressure by installation of PRVs were analysed from a minimum of one valve to a maximum of nine valves. The main results are: a) a complete division of the network into three districts does not permit a complete control of the pressure in the central part of the WDS; b) due to the configuration of the distribution system, the regulation of the pressure over the total area can be obtained by the installation of a PRV on the main pipe coming from the reservoir; c) the combination of PRV on the main pipe and realization of a district in the northern area can represent an optimal solution.

Installation of both PAT and PRV represents an interesting opportunity to recover unused energy without compromising the network functionality. It is possible to find a commercial pump that permits to produce energy with sustainable costs and an acceptable period of capital payback. The main aspects to control for selecting the optimal PAT are: a) the great variability of flow along the conduct influences the choice of BEP; b) pumps with Q_{pb} in correspondence with the maximum flow cannot work when the flow is the minimum, due to the negative values of the efficiency; c) the total costs of the PAT installation (investment and maintenance) have a great influence on the choice of the optimal solution.

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