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Procedia Engineering 70 (2014) 439 – 448

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

Energy recovery in water distribution networks. Implementation of pumps as turbine in a dynamic numerical model

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Abstract

In complex networks characterized by the presence of private tanks, water managers usually apply intermittent distribution, thus reducing the water volumes supplied to the users, or use Pressure Reduction Valves (PRV) for controlling pressure in the network. The application of Pump As Turbines (PATs) appears as an alternative and sustainable solution to either control network pressure as well as to produce energy. In the present paper, the hydrodynamic model, already presented by De Marchis et al. (2011) was further developed introducing the dynamic analysis of PATs. The model was applied to a district of Palermo network (Italy) characterized by intermittent distribution and by inequities among the user in term of water supply.

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Keywords: Pump as Turbine (PAT); water distribution network; method of characteristic; intermittent distribution; energy saving.

1. Introduction

Energy plays an important role in almost all areas of human and commercial activities. In Water Distribution Networks (WDNs), the operational costs are growing especially in most developing countries, where an increase of the water demand occurs. The energy used to pump and treat water for urban residents and industry represents the 2-3% of the world's energy consumption which could be reduced by at least 25 % through cost-effective actions. The strong connection between water and energy in WDN gives rise to programs, such as Watergy (Barry (2007)), whose aim is to realize significant energy, water and monetary savings through technical and managerial changes. Several researches were carried out in order to investigate the possibility to recover energy in water distribution networks, considering mini- and micro-hydropower plants. Unfortunately, the high equipment costs prevent them from having a widespread application in water systems. Considering that pumps are relatively cheap and simple machines, characterized by reduced maintenance cost and readily available in most developing countries, since 1930, several studies investigated the possibility to use pumps in a reverse mode, as hydraulic turbines. The studies clearly

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doi:10.1016/j.proeng.2014.02.049

showed that the use of PATs can be considered a good alternative for power generation. Despite of this, until now some issues are still open and need further analysis. Recently, Laghari et al. (2013) showed that among the renewable energy sources, large hydropower, biomass (Messineo et al. (2012)), solar heating system, wind and mini-hydro and waste-to-energy plants (Messineo and Marchese (2008)) are able to cover a significant amount of electricity demand. Unfortunately, the mini-hydro energy production represents the minor contribution despite its technology is mature, reliable and more efficient than others kind of renewable energy. Furthermore, Laghari et al. (2013) showed that almost the 60% of the installed mini-hydro capacity in the word is achieved by Chine, while Italy cover only a quote of 3 %. The huge costs of civil construction, electromechanical equipment and the long delay in approval processes suggest using PATs which have lower equipment cost in respect to the common hydraulic turbines.

One of the most interesting experimental research has been conducted by Derakhshan and Nourbakhsh (2008b), where some relations were derived to predict the Best Efficiency Point (BEP) on several low specific-speed centrifugal PATs. The experiments, where four PATs were tested, clearly showed that centrifugal pump can operate as turbine with different rotational speeds, various heads and flow rates without any mechanical problem. Singh and Nestmann (2010) carried out experimental analysis to explore wide range of PAT shapes. They accurately characterize these effects with respect to internal hydraulic variables over the complete operating region of the PAT. Furthermore they tried to develop a theoretical model that involves the external operating variables on the PAT and the internal variables, using fundamental hydraulic and turbo machine laws. More recently, Nautiyal et al. (2011) carried out an experimental investigation of centrifugal pump to study its characteristics in pump and turbine mode operation.

More recently some interesting analysis were focused to analyse reverse operation of centrifugal pumps through Computational Fluid Dynamics (CFD). Unfortunately, until now CFD techniques are not successful to predict the correct performance of PATs. Derakhshan and Nourbakhsh (2008a) compared theoretical, experimental and CFD results of a PAT but large deviations were observed between CFD and experimental results, showing that further efforts are required. A similar analysis was later achieved by Yang et al. (2012a) who, investigating on PATs performance using theoretical, CFD and experimental methods, showed that further analysis with experimental or theoretical technique are required to well capture the pump as turbine performances. This issue was also pointed out by Nautiyal and Kumar (2010) in their review on pumps working as turbine. The authors stated, in fact, that despite the intense efforts carried out by several researchers, until now, the CFD is not yet an acceptable technique. Later, on the contrary, Carravetta et al. (2012) stated that the CFD technique can be considered a valid alternative to experiment when there is a lack of the pump producers' characterization of PAT performance. Similar results were already obtained by Fecarotta et al. (2011) who compared CFD simulations and experiments, predicting the behaviour of a turbo machine both in pump and in turbine mode. However, they found that the reliability of the solution depends on the type of the flow regime condition and on the resolution of the computational grid. CFD investigations were also carried out by Yang et al. (2012b), who, comparing the experimental result with the numerical one, found that numerical results over predict the experimental data. Anyway the general trend of the efficiency, pressure head and shaft power curves were well captured.

Recently, PATs were investigated in terms of economic benefits. Arriaga (2010) presented the concept of Pump as Turbine as a viable technical and economical alternative for the further pico-hydro development in the Lao PDR located in South East Asia. Carravetta et al. (2012), through the comparison between experimental and CFD analysis, proposed a design method based on a Variable Operating Strategy (VOS) to predict the PATs behaviour and to find the optimal solution which maximizes the produced energy in WDNs. Later, Carravetta et al. (2013) extended the VOS methodology to investigate on best economic efficiency between an hydraulic regulation (HR) or an electrical regulation (ER), founding that HR is more flexible and efficient than ER. Recently, Puleo et al. (2013) analysed the PATs application in a real case through the development of an hydraulic model. They investigate on the potential energy recovery from the use of centrifugal PATs in a WDN characterized by the presence of private tanks and intermittent service. The results showed that the energy production can be low and also discontinuous, questioning its efficacy, highlighting that further studies are required to investigate the possibility and the efficiency of the PATs to recover energy from the WDN. Fontana et al. (2012) presented a management strategy with two main folds: pressure control to reduce water losses and energy production. The authors applied, in a real water distribution network, a system of PRVs and PATs. Specifically, they tried to substitute the optimal location of PRVs with PATs, showing a really attractive profits and capital payback period. Despite the efficiency of PATs is lower than conventional hydro-turbines, a recent analysis carried out by Motwani et al. (2013) and based on the comparison between the annual life cycle cost (ALCC) of a PAT and a of a Francis turbine, showed that the ALCC is very less for PAT than that of Francis turbine, thus justifying further efforts in the study of PATs applications.

The present paper analyses the potential energy recovery obtained by the use of PAT devices installed in a water distribution network with private tanks. To this aim, the Method of Characteristics (MOC), used to predict the water head and the flow rate in WDN, was improved, introducing a module able to simulate the PATs recently investigated, through experimental analysis, by Derakhshan and Nourbakhsh (2008b). The model was applied to a district of Palermo network (Italy), characterized by intermittent distribution and by inequities in user water supply. A management strategy was performed, based on the economic analysis, and the payback period was calculated.

2. Methodology

The numerical model used to investigate on the efficiency of PATs in real WDNs is the hydrodynamic model already presented by De Marchis et al. (2010) and De Marchis et al. (2011). The model was updated including a specific integrated module able to take into account PATs devices. In the following some details on the hypotheses and the equations of the hydraulic and PAT models are reported.

2.1. Hydrodynamic model

The numerical model is based on the resolution of the momentum and continuity equations, through the method of characteristic. Due to the specific feature of the proposed model, occurring especially during the phase of filling of the pipes, some simplifying assumptions were needed. Based on the Liou and Hunt (1996) study, it is assumed that the air pressure at the water front is always atmospheric and the wave-fronts are always perpendicular to the pipe axis and coincident with the cross sections. For detailed discussion of the above hypothesis see (De Marchis et al. (2010, 2011). The 1D unsteady flow of the compressible liquid in the elastic pipe is described by the following system of equations:

$$g\frac{\delta h}{\delta s} + V\frac{\delta V}{\delta s} + \frac{\delta V}{\delta t} + gJ + \frac{g}{c}V sin\theta = 0 \tag{1}$$

$$\frac{g}{c}V\frac{\delta h}{\delta s} + c\frac{\delta V}{\delta s} + \frac{g}{c}\cdot\frac{\delta h}{\delta t} = 0 \tag{2}$$

where t is the time, V is the velocity averaged over the pipe cross-section, h is the water head, g is the acceleration due to gravity, c is the celerity of pressure waves, θ is the slope of the pipeline, while

$$J = J_s + J_u \tag{3}$$

represents the head loss per unit length due to steady and unsteady friction, respectively. The steady friction contribution is calculated according to the classical Darcy-Weisbach equation:

$$J_s = \frac{f\cdot V\cdot |V|}{2\cdot g\cdot D} \tag{4}$$

where J_s is the Darcy-Weisbach friction factor and, both with the velocity V, is calculated dynamically at each time step. On the other hand, J_u, according to the formulation of Brunone et al. (1991), later modified by Vitkovsky et al. (2006), can be calculated according to:

$$J_u = \frac{k}{g}\left(\frac{\delta V}{\delta t} + c\cdot\phi_A\frac{\delta V}{\delta s}\right) \tag{5}$$

where k is a coefficient obtained dynamically in function of the flow regime, as will be shown in the following, while ϕ_a is a coefficient depending on the sign of the convective acceleration. Specifically, $\phi_A = +1$ if V $\frac{\delta V}{\delta s} \geq 0$; -1 if V

$\frac{\delta V}{\delta s}$ ¡ 0. Introducing Eq.5 into Eq.1 and applying the MOC approach, the momentum and continuity partial differential equations can be transformed into ordinary differential equations, known as compatibility equations:

$$(1+k)\frac{dV}{dt} + \alpha\frac{g}{c}\frac{dh}{dt} + gJ_s + \frac{g}{c}\alpha V sin\theta = 0 \tag{6}$$

$$(1+k)\frac{dV}{dt} - \beta\frac{g}{c}\frac{dh}{dt} + gJ_s + \frac{g}{c}\beta V sin\theta = 0 \tag{7}$$

where α and β are $\frac{k+2-k\phi_A}{2}$ and $\frac{k+2+k\phi_A}{2}$, respectively.

The compatibility equations are valid along the proper positive and negative characteristic lines of equation that, introducing the unsteady friction model, read:

$$C^+ : \frac{ds}{dt} = +\frac{c}{\alpha} \tag{8}$$

$$C^- : \frac{ds}{dt} = -\frac{c}{\beta} \tag{9}$$

In the proposed numerical model the coefficient k was calculated at each time step toward the Vardy and Brown (2003)formulation, given by:

$$k = \frac{\sqrt{c^*}}{g} \tag{10}$$

with

$$c^* = \begin{cases} \frac{7.41}{Re^{log\left(\frac{14.3}{Re^{0.05}}\right)}} \text{ for } Re \geq 0 \\ \\ 0.047 \text{ for } Re < 0 \end{cases} \tag{11}$$

The Eq.6 and 7 can be solved through the finite difference technique. Following the notation used in Fig. 1, these equations read:

$$h_j^{i,n+1} - h_{jm}^{i,n} + \frac{1+k}{\alpha}\frac{c}{g}(V_j^{i,n+1} - V_{jm}^{i,n}) + \left[\frac{c}{\alpha}J_{jm}^{i,n} + V_{jm}^{i,n} sen\theta^i\right]\Delta t_i = 0 \tag{12}$$

$$h_j^{i,n+1} - h_{jv}^{i,n} + \frac{1+k}{\beta}\frac{c}{g}(V_j^{i,n+1} - V_{jv}^{i,n}) + \left[\frac{c}{\beta}J_{jv}^{i,n} + V_{jv}^{i,n} sen\theta^i\right]\Delta t_i = 0 \tag{13}$$

where $V_j^{i,n+1}$ and $h_j^{i,n+1}$ are the velocity and the water head in the j-*th* section (of abscissa $(j-1)L_i/N_i$) of the i-*th* pipe at the time step $t^n + \Delta t$; j_m and j_v are the sections upstream and downstream to the j-*th* section, respectively.

The time step advancement Δt_i^n, function of the length and of the celerity of the i-*th* pipe, is calculated for each pipe and then the minimum value is chosen as the unique time step integration:

$$\Delta t_i^n = min_1 \Delta t_i^n = min_i\left(\frac{L_i^n}{N_i c_i}\right) \tag{14}$$

When the velocity of the water front $V_j^{i,n+1}$ is calculated, the filling process is updated according to:

$$L_i^{n+1} = L_i^n + V_N^{i,n+1} \cdot \Delta t \tag{15}$$

where L_i^{n+1} is the length of the water column inside the partially empty i-*th* pipeline at the time t_n+1. The compatibility equations for the pipelines connected to the node are resolved together with the continuity equation at each

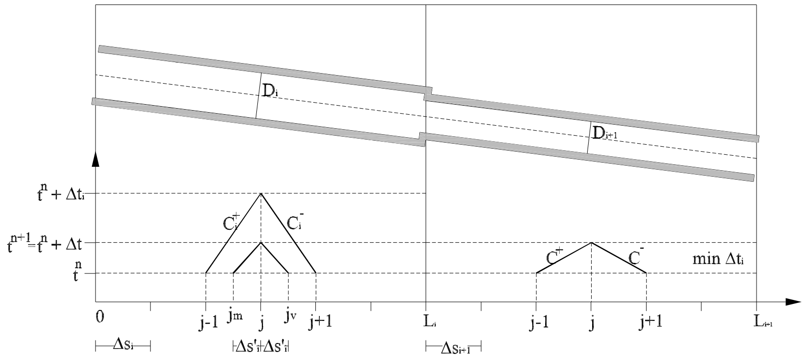

Fig. 1. Space-time scheme for two-pipe of different diameter with the same number of section N and different time step Δt_i

junction node, and the discharge provided to user tanks is calculated as a function of the water head. Specifically, the discharge $Q_{j,up}$ at the j-*th* node entering the tank connected to the node can be obtained as:

$$Q_{j,up} = C_v A \sqrt{2g \cdot (h^i_j - h_{j,tank})} \tag{16}$$

where C_v is the non-dimensional float valve emitter coefficient, A is the valve effective discharge area, h^i_j is the water head at the j-*th* node and $h^i_{j,tank}$ is the height of the private tank. Although more complex methods were considered in the past to relate coefficients C_v and a to valve-opening rates, here constant values were used for both of the coefficients (see, Criminisi et al. (2009)) which have been calibrated experimentally.

2.2. PAT module

As previously discussed, the hydrodynamic model is coupled with a numerical module able to reproduce the PATs installation in the pipes of WDN. In the present analysis, several manufacturers catalogues were investigated to identify pumps satisfying the given turbine operating conditions (head and flow). The characteristic curves achieved by Derakhshan and Nourbakhsh (2008a) and Derakhshan and Nourbakhsh (2008b) through experimental analysis were applied. Specifically, dimensionless head and power curves of a PAT can be estimated using the equations:

$$\frac{H_t}{H_{bt}} = 1.0283\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468\left(\frac{Q_t}{Q_{tb}}\right) + 0.5314 \tag{17}$$

$$\frac{P_t}{P_{bt}} - 0.3092\left(\frac{Q_t}{Q_{tb}}\right)^3 - 2.1472\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865\left(\frac{Q_t}{Q_{tb}}\right) + 0.0452 \tag{18}$$

where H (m), P (W), Q (m^3/s) are head, power, flow rate, respectively. Subscripts t and b are related to turbine and Best Efficiency Point. Following, among others, Derakhshan and Nourbakhsh (2008a) and Derakhshan and Nourbakhsh (2008b), the PATs parameter are related to the specific rotational speed n (rps). Specifically, dimensionless head, discharge and power curves can be obtained through the equations:

$$\phi = \frac{g \cdot H}{n^2 \cdot D^2_{imp}}; \qquad \psi = \frac{Q}{n \cdot D^3_{imp}}; \qquad \pi = \frac{P}{\rho \cdot n^3 \cdot D^5_{imp}} \tag{19}$$

where D_{imp} is the impeller diameter.

The BEP is achieved maximizing the efficiency according to the equation:

$$\eta = \frac{P_{tb}}{\rho \cdot g \cdot Q_{tb} \cdot H_{tb}} \tag{20}$$

As suggested by Derakhshan and Nourbakhsh (2008a) the prediction method is acceptable for centrifugal pumps with N (rpm) ≤ 60.

With the aim to combine water saving with current renewable energy policies, PATs are coupled with Pressure Reducing Valves (PRVs).

3. The case study

The proposed numerical model has been applied on one of the 17 distribution networks of Palermo city (Sicily), designed to deliver about 400 l/capita/d but the actual mean consumption is about 260 l/capita/d that supply around 35,000 inhabitants (11300 users). The network was built by polyethylene pipes and their diameters ranging from 110 to 400 mm. Additional details on the analysed network can be found in De Marchis et al. (2010). The current configuration of the network is characterized by significant inequality in the distribution of water resources during intermittent supply. As demonstrated by De Marchis et al. (2010), the WDN can be subdivided in two main regions by geodetic elevation. To improve the clarity, in Fig. 2 the sub-network characterized by lowest elevation has been delimited through dotted lines, while the highest geodetic region is indicated through a continuous line. The network orography suggests the possibility to introduce some PATs in the network pipes connecting the two main regions. The PATs, reducing the head, should also reduce the inequality among the users. As demonstrated by De Marchis et al. (2011), in fact, in the deepest network zone the user supplies is particularly higher than the disadvantaged nodes.

The analysed WDN is characterized by six pressure cells and two electromagnetic flow meters (Fig. 1). The pressure data were used for model calibration and validation, showing the ability of the proposed hydraulic model to reproduce the behaviour of a real network (see De Marchis et al. (2010, 2011) for the validation tests. As can be observed in the Fig. 2, the two sub zones are connected by mean of three main pipes, one located close to the supply node, the second located in a middle zone, while the third is about 1.5 km far from the inlet node. Several numerical experiments were carried out to evaluate the convenience of PATs installation. Here the results of four tests are analysed. Specifically, in the test case 1, as shown in Fig. 3a the PAT has been simulated in the pipe connected to the supply node, having a diameter of 400 mm. In the second test case shown in Fig. 3b, the PAT has been installed in the pipe of the network closest to the inlet node, having a diameter of 150 mm. The third scenario is referred to the PAT installed in the connection pipe, between the highest and lowest geodetic sub-zone, located in the middle of the WDN, see Fig. 3c. Finally, in the last test case the PAT is installed in the pipe, linking the two sub network, far from the supply node as shown in Fig. 3d.

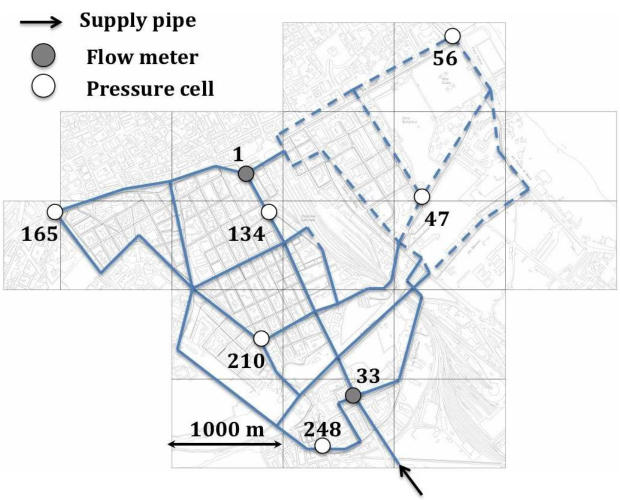

Fig. 2. Case study network scheme. The continuous blue line delimits the region with the highest elevation, the dashed blue line delimits the region with the lowest elevation.

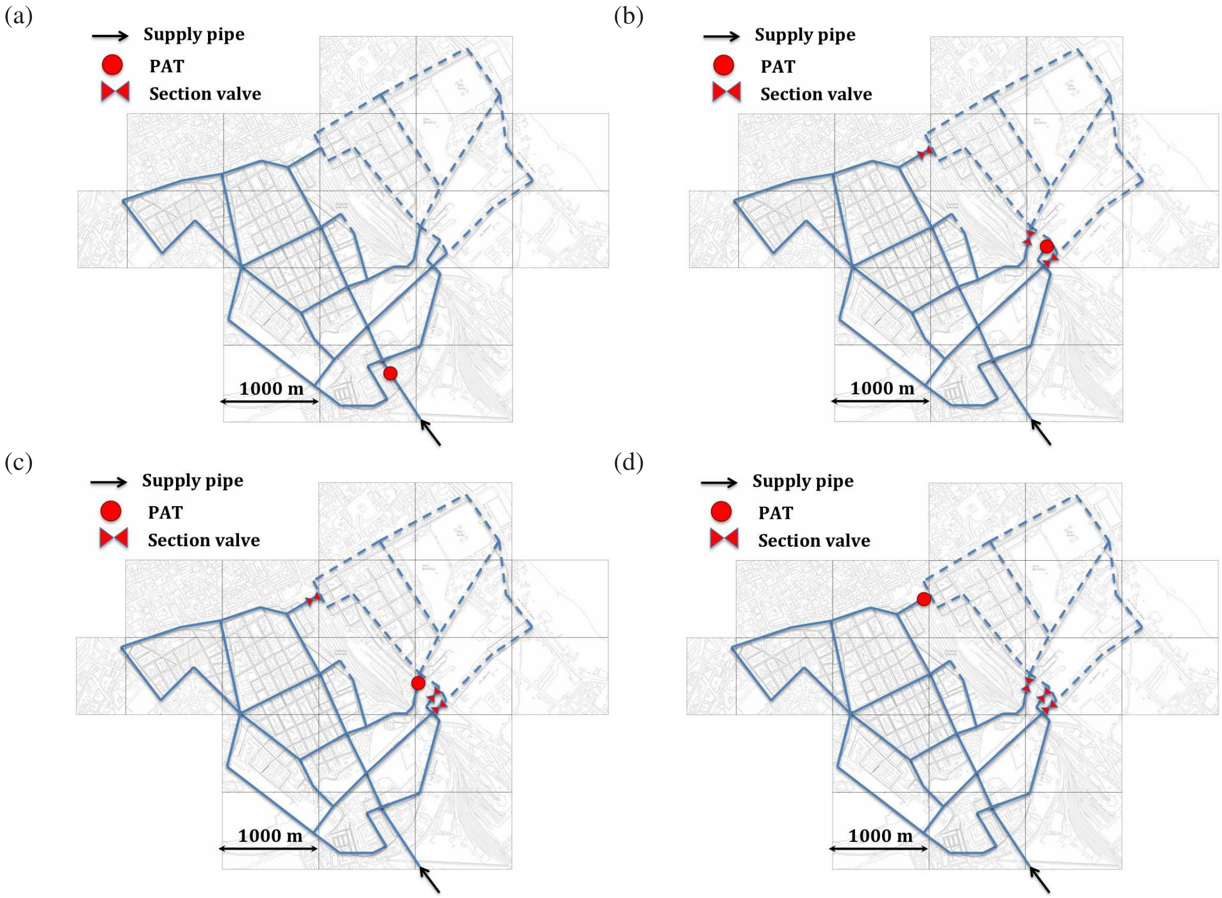

Fig. 3. Position of the PATs and closed pipes on network mains: Test case 1 (a), test case 2 (b), test case 3 (c) and test case 4 (d). The blue lines are highlight the boundaries of the two main region of the network.

4. Results and discussions

The analysis here reported is aimed to check the validity of the installation of PATs in real WDN through numerical modelling. With the aim to reduce the cost of installation and maximize the PATs efficiency, a numerical model able to guide the water managers should be very attractive. In the following, a preliminary analysis is discussed in light of the capital payback period, exploring the four different position of installation specified in the lass section. The economic analysis has been carried out considering a produced energy cost equal to 0.22 euro/kWh, as it is the average value for the renewable produced energy in Italy. The Energy Generation Equipment (EGE) has been evaluated taking into account the PAT cost, the generator cost and the related electrical equipment. The PAT cost has been calculated according to the BEP of the power of the PAT. Specifically, based on market analysis, the EGE cost has been estimated considering 2000 euro/kW for each turbine power installed P_{inst}. The Civil Works cost (CW) should be added too. According to Fontana et al. (2012) CW has been calculated 30 % the EGE costs. In order to make a preliminary but complete analysis of capital payback period (CPP), the maintenance costs MC have to be considered. In literature, it is suggested a quote range between 10-15% of the total cost (EGE+CW). Here the highest value is chosen. The CPP is thus calculated as the ratio between the total installation cost (EGE+CW) and the Annual Finantial saving (AF)

expressed in euro/year. AF is calculated as the product of the energy cost (0.22 euro/kWh) and the Average Yearly Energy Production ($AYEP$) subtracting the MC (see Eq.21).

$$CPP = \frac{EGE + CW}{AF}; \qquad AF = 0.22 * AYEP - MC; \qquad MC = 0.15 \cdot (EGE + CW) \tag{21}$$

Table 1. Economic feasibility of PATs installation in a WDN: Cost and capital payback period analysis .

Test case	P_{inst} (*kW*)	AYEP (*kWh/year*)	EGE (*euro*)	CW (*euro*)	MC (*euro*)	AF (*euro/year*)	CPP (*years*)
Test case 1	8.59	65,156	17,176	5,152	3,349	10,984	2,03
Test case 2	1.88	12,763	3,764	1,129	734	2,073	2,36
Test case 3	3.55	19,740	7,098	2,129	1,384	2,958	3,12
Test case 4	2.62	10,019	5,247	1,574	1,023	1,181	5,78

Table 2. PATs characteristic in turbine mode.

Test case	Q_{tb} (m^3/s)	H_{tb} (m)	P_{tb} (kW)
Test case 1	0.16	6.27	7.30
Test case 2	0.026	8.43	1.60
Test case 3	0.038	10.9	3.02
Test case 4	0.033	10.4	2.23

In Table 1 the costs for the four scenarios are summarized. In the above analysis the PAT power installed P_{inst} was calculated starting from the P_{tb} and considering an overall efficiency of 85%.

In Table 2 some details on the BEPs of the four test cases are added.

The results of the economic analysis show a general efficiency of the energy recovery, with an attractive payback period almost 2.5 years, at least for the scenario 1, 2 and 3. Similar results were obtained by Fontana et al. (2012). As shown in Fig. 3, in these three test cases the PATs are located in pipes close to the supply pipe. This should be attributed to the higher discharge values than the test case 4. In this last case, in fact, a CPP almost twice of the first three installation is verified. In the four case the PAT has been installed in a pipe located far from the inlet node, thus the lower energy production can be attributed to reduced flow rate driving through. The Average Yearly Energy Production (AYEP) values, reported in Table 1, were calculated integrating the energy production during a 24-hour simulation describing the average yearly conditions. The energy production time series for all test cases are reported in Fig. 4. As it can be observed in the figure, at 5:00 a.m., where the minimum value of averaged daily user demand is achieved, the lowest energy production is verified in all cases. This is clearly due to the fact that the reduced consumptions cause a reduced flow rate in the WDN. It is interesting to observe that despite in the test case 1 the higher values of energy production are registered, the CPP is almost the same of the test case 2. The increase of the P_{inst} generate an augmentation of EGE and MC costs. This is a clear evidence that a preliminary detailed analysis of the network in term of energy production, should be very attractive to maximize the overall system efficiency. As shown in the Fig. 4, the PATs were activated after two hours from the beginning of the simulation. Thus, the period of the pipes filling process was neglected. Obviously, in water distribution system characterized by continuos supply the economic benefits should increase. In order to check the effect of the PATs installation among the users in Fig. 5 the values of the water volume supplied at each node, for the different test cases here considered is plotted. To improve the clarity the test case TC_0, where the numerical model runs without PAT installation, is added too. It can be observed that the test case 2 seems to be the best choice in term of water resources. The total water resources supplied to the users in the test case 2 is, in fact, the 85% of the total water volume supplied in the TC_0. In the TC_1 the service percentage is reduced to the 80%. This could be attributed to the global pressure reduction occurring in all the network, when the PAT is installed in the inlet pipe. In the TC_3 and TC_4 the PATs increase the supply to the 77% and 74%, respectively. Fig. 5 shows that the TC_2 installation causes a drastic reduction of water supply in the nodes 25 to 35, while these nodes are not affected by water reduction in the test cases 3 and 4. In the nodes from 70 to 80 the opposite holds. This particular condition suggests to explore the possibility to install PATs working alternatively.

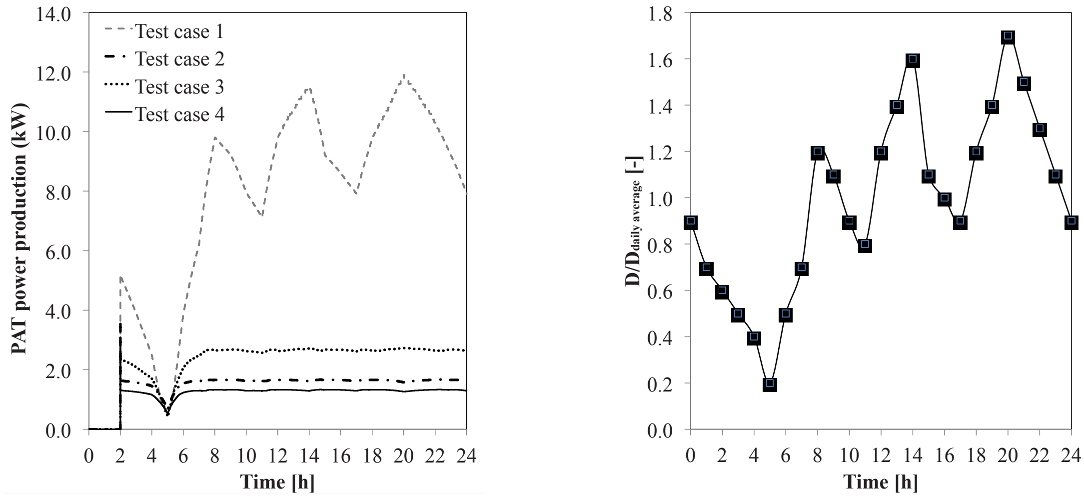

Fig. 4. Left: Power production for the four test cases. during 24-hour simulation. Right: Average daily user demand pattern adopted in the numerical simulations.

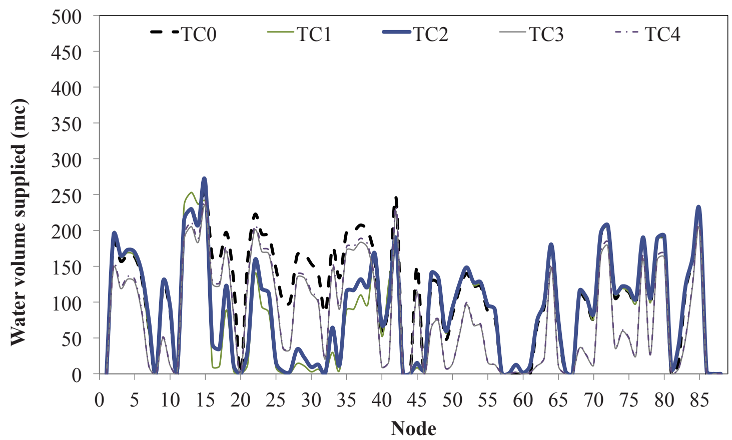

Fig. 5. Water volume supplied in each node during a day. Case TC_0 represents the case without PAT installation.

Some analysis are focusing on this issue, thus to maximize the PATs efficiency and reduce the inequities in the water resource. Despite the present analysis can be considered only a preliminary investigation, some really interesting features were pointed out, showing that PATs installation can be considered strategic in terms of renewable energy production.

5. Conclusions

In the study, a dynamic mathematical model for intermittent networks was integrated with a model able to analyse the presence of PATs in water distribution network. The model demonstrated to be robust and to correctly represent the impact of energy recovery on water supply distribution. Four different scenarios were analysed involving PATs 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. The analysis showed that a really attractive capital payback period can be achieved, if the PATs are installed in the pipes located close the water supply node. In this case, in fact, coherently with some literature findings, CPP of about 2.5 years was achieved. The maximum efficiency can be reached is the PATs are installed in the main pipe, despite the highest cost of installation and maintenance. The economic benefits are considerably reduced when the PATs are placed in disadvantage pipes, in term of discharge. In the test case 4, where the PAT is installed far away from the inlet node, the CPP is almost twice the others cases. The results obtained are dependent on the specific case of study and further validation should be provided by additional monitoring and through the comparison of the numerical simulations with a field survey. Nevertheless, the preliminary results show the attractiveness of the numerical model to evaluate the best PATs position.

Acknowledgements

The Authors would like to acknowledge the Italian Research Project POR FESR Sicily 2007-2013 - Measure 4.1.1.1 *SESAMO - SistEma informativo integrato per l'acquisizione, geStione e condivisione di dAti aMbientali per il supportO alle decisioni* for providing financial support to the presented research.

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