PRODUCIBLE ENERGY AT THE INLET POINT OF A DISTRICT BY REPLACING A PRESSURE REDUCING VALVE WITH A PUMP RUNNING IN TURBINE MODE

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KEY POINTS

- *Collection of pressure and discharge field data at the inlet point of a DMA.*
- *Estimation of pump and PAT (pump as turbine) performance curves from literature data.*
- *Assessment of the producible energy by installing a PAT at the inlet point of the DMA.*
- *Calculation of the conversion efficiency, for both the entire system and the PAT alone.*

1 INTRODUCTION

Water distribution networks (WDNs) are generally affected by leakages, which are strictly dependent on pressure. Pressure control thus represents an effective action that can be performed in order to reduce leakages (*Araujo et al.*, 2006). Operatively, pressure control in WDNs can be achieved by creating district metered areas (DMAs) (*Alvisi*, 2015) and/or placing Pressure Reducing Valves (PRVs) to prevent the downstream hydraulic pressure from exceeding the desired value. PRVs are variable closure devices that reduce the conveyance capacity of the pipe by increasing the pressure losses (*Giugni et al.*, 2009). However, in the framework of a virtuous energy policy, any attempt should also be made by water network managers to convert energy dissipation into energy production (*Carravetta et al.*, 2012). To this end, as highlighted in *Sammartano et al.* (2013), among the different turbines that can be coupled with low and variable power, Pump As Turbines (PATs) can be considered a good alternative, since they combine low installation costs with an acceptable energy production. Indeed, pumps can be used in turbine mode by reversing flow direction with the engine acting as a generator (*Ramos & Borga*, 1999).

One of the main challenges is that pump manufactures do not usually provide the performance curves of pumps in reverse operation and the designer usually faces a lack of data that constitutes an obstacle to the choice of the most suitable machine. Therefore, establishing a correlation that enables the transfer from "pump" characteristics into "turbine" characteristics is crucial. Many researchers have presented some theoretical and empirical relationships for predicting the Best Efficiency Point (BEP) of a PAT (e.g. *Derakhshan & Nourbakhsh*, 2008) and also the entire performance curves a PAT on the basis of the performance curves of the respective pump (e.g. *Venturini et al.*, 2017a and 2017b).

In this framework, this paper evaluates the producible energy at the inlet point of a DMA where a PRV is actually installed, by simulating the replacement of that same PRV with a PAT. To this end, nine different PATs, of which the performance curves over the entire range of operation are taken from published data reported in technical literature (*Barbarelli et al.*, 2017). Thus, this paper reports an estimation of the producible electric energy and the corresponding conversion efficiency from the available hydraulic energy. In the following, the case study and the pump and PAT performance curves are introduced. Then, the results of the analysis of PATs' energy potential are presented and discussed. Finally, conclusions are provided.

2 MATERIALS AND METHODS

2.1 Case study

The case study is represented by a DMA located in northern Italy which serves around 1000 users and whose total pipe length is about 50 km. The DMA is connected to the water main system in just one point, where a PRV is currently located in order to reduce the downstream pressure, since the pressure within the water main is considerably higher than that required within the distribution system. Indeed, within the DMA the pressure is fixed at approximately 35 m, while the pressure within the main varies from about 45 m to 125 m leading to head drops (H) at the PRV varying between 10 m and 90 m. The discharge (Q) entering the DMA varies between 2 L/s and 26 L/s. Available field data of discharge and head drop refer to one year of operation and were collected every 15 minutes for a total of 35,040 measured data sets (see figure 1).

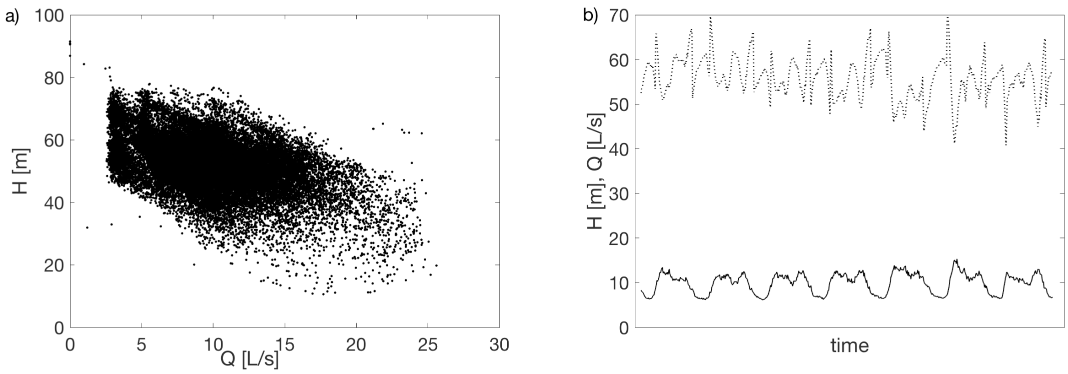

Figure 1. (a) Available head drop (H) vs. discharge (Q) at the inlet point of the DMA for one year and (b) example of the trend over one week of the discharge entering the DMA (continuous line) and corresponding head drop (dotted line).

2.2 Pump and PAT performances curves

The considered pump and PAT performance curves were derived from *Barbarelli et al.* (2017), which documented the performance data taken experimentally on several turbomachines running in both pump and PAT mode. Table 1 reports the main geometrical characteristics of the considered pumps (i.e. discharge nozzle and impeller diameter) and the operating ranges. All the pumps are characterized by a rotational speed equal to about 1450 rpm and specific speeds, defined as $\omega Q^{0.5}/(gH)^{0.75}$ (ω [rad/s]; Q [m^3/s]; H [m]), ranging from 0.17 to 1.21. It can be seen that the considered pumps can swallow up to 38 L/s (pump #9), with a maximum head of 40 m (pump #4) and maximum efficiency of 74% (pump #8). Instead, the maximum volume flow rate allowed for PAT operation is higher than that of the pump (i.e., 47 L/s for PAT #9). The required head is rather different for the nine PATs, e.g., it is in the range 8–15 m for PAT #5 and 37–153 m for PAT #3. Moreover, it should be noted that, unexpectedly, the maximum value of efficiency in PAT mode is generally higher than the maximum efficiency in pump mode.

In this paper, pump and PAT performance curves are modelled independently, by interpolating the experimental data reported in *Barbarelli et al.* (2017). A functional dependence by means of a second-order polynomial was used for the three non-dimensional performance parameters ψ (non-dimensional head), π (non-dimensional power), and η (efficiency), as a function of the non-dimensional volume flow rate (φ).

	Discharge nozzle (mm)	Impeller diameter (mm)	PUMP			PAT		
			Q (L/s)	H (m)	η(%)	Q (L/s)	H (m)	η(%)
#1	40	200	0 – 9	3 - 14	0 - 55	4 - 16	12 - 59	7 - 59
#2	40	250	0 - 11	10 - 23	8 - 55	0 - 16	17 - 81	4 - 51
#3	40	315	0 - 8	28 - 37	0 - 45	5 - 17	37 - 153	4 - 35
#4	40	335	0 - 10	20 - 40	1 - 44	8 - 18	50 - 151	19 - 43
#5	50	160	1 - 15	7 - 10	25 - 67	8 - 17	8 - 15	45 - 73
#6	65	250	0 - 28	7 - 22	1 - 64	9 - 40	17 - 79	3 - 65
#7	80	200	0 - 30	10 - 14	0 - 72	4 - 41	8 - 27	19 - 76
#8	80	220	0 - 32	12 - 17	1 - 74	5 - 43	9 - 29	12 - 78
#9	80	250	0 - 38	14 - 23	2 - 73	14 - 47	16 - 51	3 - 72

Table 1. Pump and PATs characteristics.

3 RESULTS

The analyses carried out in this paper were developed in order to assess a) the energy potential of otherwise-wasted hydraulic energy and b) the conversion efficiency of energy recovery, for both the entire system (overall efficiency) and for the PAT alone (PAT efficiency).

In more detail, the yearly producible electric energy is obtained by considering the actual PAT working point for each data set. The working point is set by acting on two valves which should be installed together with the PAT: one valve in series with the PAT, to dissipate the excess pressure/head, and one valve in parallel (bypass valve), which can be opened to reduce the volume flow rate through the PAT. This regulation strategy was also discussed and investigated in (*Fecarotta et al.*, 2015), where it was identified as "hydraulic regulation", and represents a feasible operation mode for WDNs. It is clear that the possibility of varying PAT's rotational speed and consequently moving PAT's characteristic curve in order to match, at each time point, the available head and flow rate, may increase the producible electric energy, but would require the use of an inverter and a more sophisticated regulation system.

The producible yearly electric energy by means of the nine pumps running in turbine mode is reported in Figure 2. It can be seen that two PATs would lead to an energy production significantly higher than the other seven PATs (maximum value: 14.2 MWh). It is worth noting that both these pumps are characterized by a combination of the smallest discharge nozzle and smallest impeller diameter, which thus allow matching the available head and discharge (figure 2). However, in absolute terms, the producible yearly electric energy is rather low. For instance, the producible yearly electric energy can be compared to the residential electricity consumption per capita in 2010 in the EU-27, which was equal to 1682 kWh (*Bertoldi et al.*, 2012). Thus, in the best case, the electric energy demand of around 9 household users can be met.

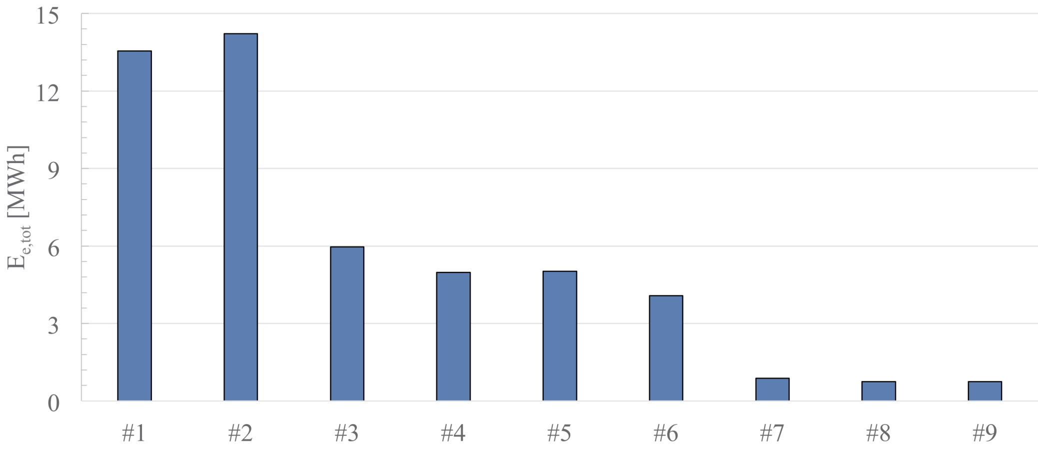

Figure 2. Producible yearly electric energy.

The rather low producible yearly electric energy can be explained by considering that a large amount of head is dissipated and quite a lot of the discharge is by-passed. This is due to the considered installation scheme and regulation system, which makes use of two valves to dissipate excessive pressure and discharge at fixed rotational speed. Indeed, larger amount of available head and discharge could be exploited by considering an electrical regulation of the rotational speed, even though recent studies pointed out that the latter approach is, on the whole, less efficient and convenient than the former (*Carravetta et al.*, 2013).

As far as the efficiency concerns, the estimation is carried out by considering both the energy potential from the whole WDN (i.e., available discharge and head drop) and PAT internal efficiency. In fact, the former conversion efficiency (overall efficiency) accounts for the incomplete exploitation of discharge and head drop, while the latter (PAT efficiency) accounts for the fact that the producible electric energy was calculated by considering the actual operating point per each data set (i.e., per each available time point), which, in general, can be considerably far from the BEP.

In particular, the overall conversion efficiency for the best solution in terms of producible energy (PAT #2, see figure 2) is approximately 33%, even though the PAT itself usually runs with an "acceptable" efficiency being the yearly average efficiency of PAT #2 around 45%. This means that the WDN potential is rather unexploited. This result is in agreement with similar analyses carried out in *Fecarotta et al.* (2015) and *Venturini et al.* (2017c) by considering several WDNs: in fact, in these studies, it was found out, that only in few cases, the overall efficiency was higher than 40%. Higher overall efficiency could be achieved using devices such as the Power Recovery System (PRS) proposed by *Sinagra et al.* (2017). Indeed the PRS includes in a single device the function of the control and by-pass regulating valve required by the PAT for the hydraulic regulation, generally allowing for higher overall efficiency, up to 60% (*Sinagra et al.* 2017).

4 CONCLUSIONS

This paper presented an energy analysis aimed at estimating the energy potential of pumps used as turbines (PATs) in order to exploit the available hydraulic energy at the inlet point of a DMA of which the experimental head drop and discharge data over one year were available. Nine pumps, of which the performance both as a pump and as a turbine were known from published experimental data, were tested.

By considering the actual variability of flow rate and available head over one year, the optimal PAT was identified and the consequent producible electric energy was estimated. The average conversion efficiency was also estimated, for both the overall system and the PAT. It was found out, that from an overall perspective, the system potential is usually rather unexploited being the conversion efficiency of 33%. Indeed, a considerable amount of head drop and/or discharge has to be wasted because of the highly variable discharge and head drop observed at the inlet of the district. In fact, the PAT itself usually runs at "acceptable" efficiency values (around 45%).

For these reasons, future works will analyze the performance of different PATs coupled with different installation and regulation schemes, in order to maximize the producible electric energy.

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