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Pump-as-Turbine for energy recovery applications: the case study of an aqueduct

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Abstract

Pump-as-Turbine (PaT) technology is taking the field in different small-hydro or energy recovery applications. These machines can be installed in water distribution grids to have pressure levels adjustment and electrical energy production. A PaT working in turbine mode has a different best efficiency point due to a variation of the fluid-dynamic operating conditions. In this paper, laboratory tests are performed to investigate its performances in pump and turbine mode. Hydraulic efficiency, torque and mechanical power are evaluated in several load conditions. In conclusion, an energy evaluation is shown considering a test case of a water distribution grid.

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Keywords: Small-scale hydropower; Energy recovery; Pump-as-Turbine; Energy efficiency; Real case study

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1. Introduction

Over the years, different kinds of technologies are being applied in order to sustain the electrical demand by the use of renewable energy sources in spite of hydrocarbon fuels. Among these sources, hydropower is the most known and established technology because it is long since used in countries where morphological conditions and water availability are suitable for its use. Hydropower is currently producing about 16% of the World electricity [1] and it is one of the main sources of electrical energy in several countries located mainly in the northern part of Europe [2] and in Canada [3]. Nowadays the large hydropower generation is quite mature and most of the large water resources and geodetic

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heights have been already exploited. Small-scale hydropower has been studied in the last decades and it is considered a solution for the electricity production in rural and remote zones where the electrical grid cannot be built. Its application can be also extended to other sectors for achieving: i) reduction of pollutants released in the atmosphere, ii) production of electricity that leads to economic benefits. These purposes are fundamental to meet environmental requirements discussed from the Kyoto Protocol to the Copenhagen Accord [4] and to achieve economic savings, discussed in the European Parliament [5], by means of renewable energies. Small-scale hydropower is taking the field for recovering and saving energy in several plants and processes. The main principle is to exploit the pressure gradient available in aqueducts and from particular chemical processes, for instance those running in oil refineries, for turning it into electric energy. Several technologies are used to this purpose: Turgo turbines, Cross-flow turbines and Agnew turbines are the most used. Turgo turbine is an impulse turbine designed for medium head applications. Cobb et al. [6] worked on the improvement of Turgo turbine efficiency studying mainly results obtained in the variation of the speed ratio and the jet misalignment. Cross-flow turbine is a machine where the water passes through the turbine transversely or across the turbine blades. After passing to the inside of the runner, it leaves on the opposite side going outward and the passage through the runner twice provides an additional efficiency. Sammartano et al. [7] showed that the installation of a certain number of Cross-flow turbines in an aqueduct could lead to a partial energy recovery by transforming pressure dissipations to electrical energy. Agnew turbine is a 45° axial flow Kaplan type used in micro hydroelectric power designed without guide vanes, under low head and limited flow potentials. Since 1930, several studies have been performed on the application of different pumps used in reverse mode as hydraulic turbines showing that Pumps-as-Turbines (PaTs) can be considered a good alternative for power generation [8] taking into account both practical and economic evaluations [9]. Agarwal [10] outlined the advantages of using PaTs instead of micro hydropower turbines: larger range of heads and flow rates use, easier availability of spare parts like seals, bearings and easier installation. Along the same line, Williams [11] stressed on economic and practical advantages for using PaTs mainly in medium head sites in spite of micro hydro turbines. This technology seemed to be the most suitable to be improved and to be modified in spite of others due to the possibility of its use in several applications and to its cost that is less expensive than turbines. Moreover, in industrial plants PaTs can be used in both pump and turbine mode depending on the process requirements. De Marchis et al. [12] stressed on the use of this technology because PaTs can substitute pressure reduction valves to control the pressure level in water distribution grids and, at the same time, to produce electricity. In later years, chemical industries, especially oil refineries, started to use PaTs for energy recovery. In an oil refinery, there are particular hydrocarbon processes where this kind of technology can be applied; these processes imply the decrease of the pressure level of a fluid stream that a PaT can perform instead of a throttling valve. Gopalakrishnan [13], along the same line of Wildner and Welz [14], explained in detail chemical processes where PaTs can be used taking into account a real case study of a refinery in Kentucky and in China, respectively. In literature, Williams [15], Stepanoff [16], Krivchenko [17], Sharma [18] and McClaskey [19] elaborated different mathematical equations for evaluating the Best Efficiency Point (BEP) of a PaT used for small-scale hydroelectric power generation by means of experimental results performed with laboratory tests and statistical evaluations. These theoretical equations were applied to predict the possible BEP of the selected pump running in turbine mode. Fig. 1 shows a possible scenario of BEP values referring to small-scale machines; as Fig.1 points out, BEP values are different one from each other due to the different typology and to the different size of pump used.

Water distribution grid is another application where PaTs can be used: a water distribution grid supplies fresh water to both householder and industrial consumers: about 32% of water is lost along the distribution grid in Italy [20] and this kind of loss affects the availability of the water source and causes, on the economic point of view, monetary expenses. Therefore, the reduction of this kind of loss can lead to preserve the water source and to economic savings because the energy supplied by pumps, needed to pump the water into the grid and to distribute it to consumers, will be lower if the water source is preserved. Along the same line, also the carbon footprint, caused directly or indirectly by the clean water distribution activities, will be decreased.

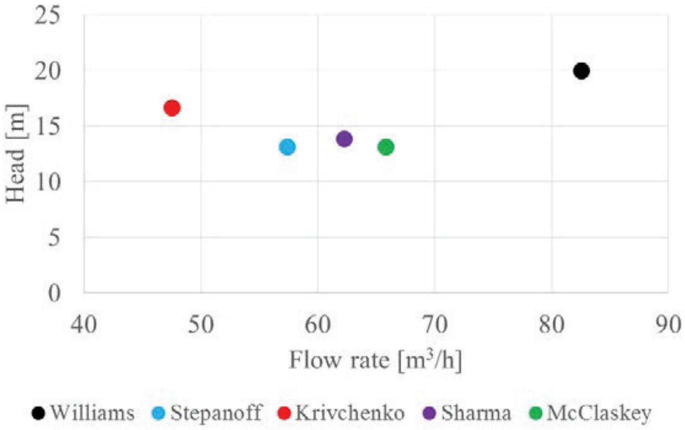


Fig. 1. Scenario of possible BEP values achieved by the selected pump

Table 1 shows methods commonly practiced for the direct containment of water losses [21]:

Table 1. Main control activities of a water distribution grid

ACTIVE CONTROLS	PASSIVE CONTROLS
Pressure control in the water distribution grid.	Research of the points where losses occur.
Periodic inspections of wells where the equipment is installed.	Periodic resurfacing of piping sections.

In the last decade, due to the increase of the cost of non-renewable sources and a greater sensitivity to environmental issues, the possibility to recover kinetic energy from the water by installing turbines on the supply pipelines of mountain aqueducts is taking the field. These turbines can be installed instead of pressure regulation valves that have the aim to control the pressure levels in the water distribution grids. Although this approach is already applied in other European countries, such as Switzerland, in Italy and in South-Tyrol its exploitation is still far from the potential level of application. Hydraulic turbines can be installed for recovering energy but they have to be designed taking into account the place where they will be installed. At the same time, their design could be complex and their cost could be high [22-24].

Through the use of PaTs, users have a wide range of choice of relatively inexpensive cost machines that can ensure the best performance in specific work conditions [25, 26]. The installation of these machines in water distribution grids implies a continuous variation of the machine working point and, therefore, it requires specific solutions to track the optimal working point for a determined situation, not affecting the electrical grid security. In this paper, a centrifugal pump was chosen in order to perform tests to study and analyse its performances in turbine mode. Subsequently, the representation of the characteristic curve in turbine mode, obtained through laboratory tests, are reported. A non-dimensional analysis, taking into account the PaT running in turbine mode, is performed in order to select a PaT that can be used in a part of the aqueduct of the city of Merano (BZ) located in South-Tyrol. Finally, an evaluation of the energy produced by the use of this technology is presented.

2. Research and methods

2.1. Test bench

Laboratory tests were performed in order to study the performance of a centrifugal pump running in reverse mode. Table 2 shows main characteristics of the main components used to perform laboratory tests.

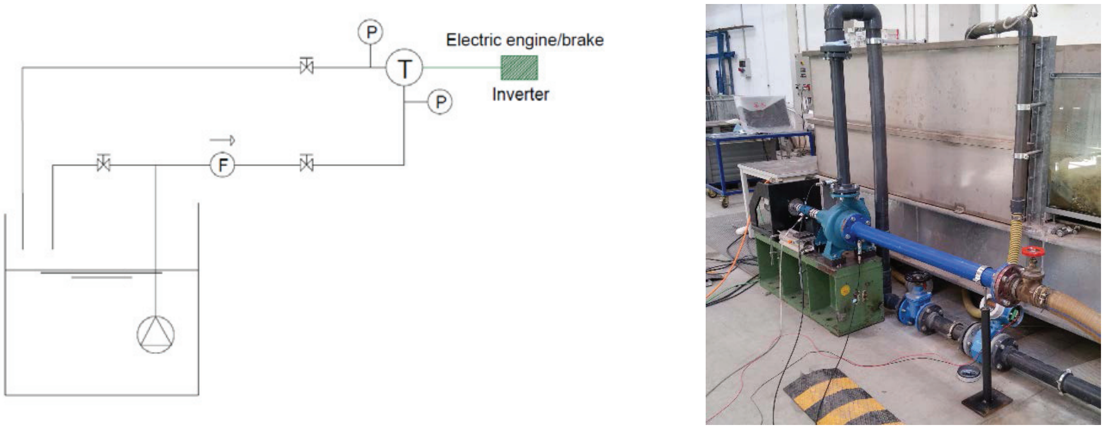
Table 2. Characteristics of the main components used to perform laboratory tests

Measured quantity	**Measurement equipment**	**Range**	**Accuracy**	**Output signal**
Flow rate	Endress+Hauser Promag 50W	0.3-10 m/s	0.5% (0.2% optional)	4-20 mA
Pressure	Keller PA33X	0-10 bar	0.1% FS Error band (10-40°C)	0-10 V
Torque	Kistler Type 4503A50	0-50 Nm	0.1-0.2%	0-5 V

A pump was selected in order to run the PaT and its main characteristics are listed in Table 3. Fig. 2 shows the sketch of the test bench (a) and the real test bench (b) used to perform laboratory tests.

Table 3. Main characteristics of the pump used to move the PaT

Flow rate value at the Best Efficiency Point (BEP)	60 m^3/h
Head at the Best Efficiency Point (BEP)	21 m
Best efficiency value	0.72
Fixed rotating speed	2,900 rpm
Specific speed	0.75
Diameter of the impeller	135 mm
Liquid processed	H_20 ($\rho \approx 1,000$ kg/m^3)

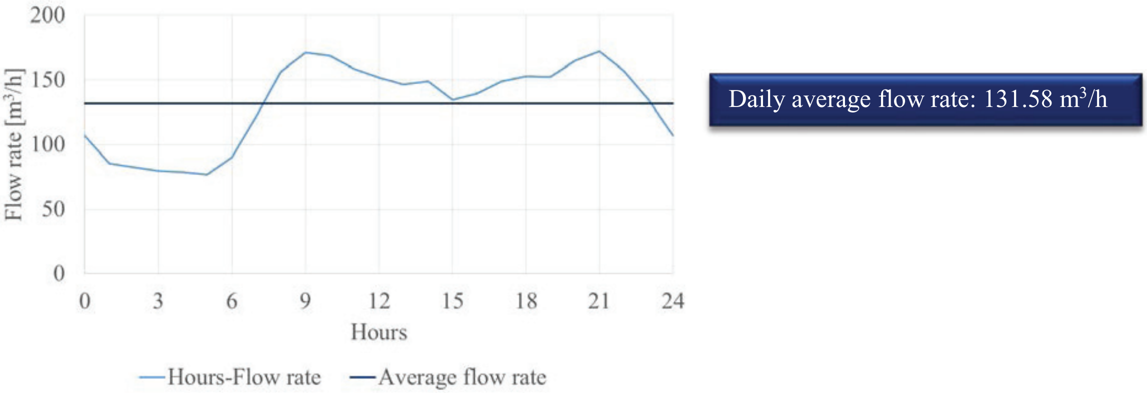


(a) (b)

Fig. 2. Sketch of the test bench (a) and the real test bench (b) used for performing tests on the selected pump in turbine mode

2.2. Case study

In this paper, a real case study of an aqueduct was performed. The water distribution grid of the city of Merano (BZ), located in South-Tyrol (39,296 inhabitants), was selected as a possible application where a PaT can be installed in order to substitute the pressure regulation valves and to recover a significant amount of energy: a single tank of the aqueduct that supplies the center of the city of Merano, where 30% of the entire population lives, was considered. Data were obtained through a measurement campaign performed during all days of April 2016. The pressure that must be available downstream the PaT is 4 bar in order to ensure the water distribution to users. The tank, where the water is collected, is located at a geodetic height close to 100 m above the town, which ensures the exploitation of the water resource. Fig. 3 shows the hourly trend of the water flow rate, during an entire day, that this tank supplies to a part of the inhabitants; in the same graph, the daily average flow rate, equal to 131.58 m^3/h, was also evaluated.



Daily average flow rate: 131.58 m^3/h

Fig. 3. Hourly trend of the water flow rate and the average flow rate

2.3. Pump selection

A centrifugal pump was selected in order to investigate its performance in turbine mode. The choice of the pump was made in order to be installed in the abovementioned water aqueduct in partial substitution of pressure regulation valves. As the effective dimension of pump would be too big to be installed in the described test bench, a smaller machine working in fluid-dynamic similarity conditions compared to that which will be installed in the site was considered. The main characteristics of the pump are listed in Table 4 while the dimensional characteristic curve and the dimensional power curve, taking into account the data sheet of the pump itself, are reported in Fig. 4.

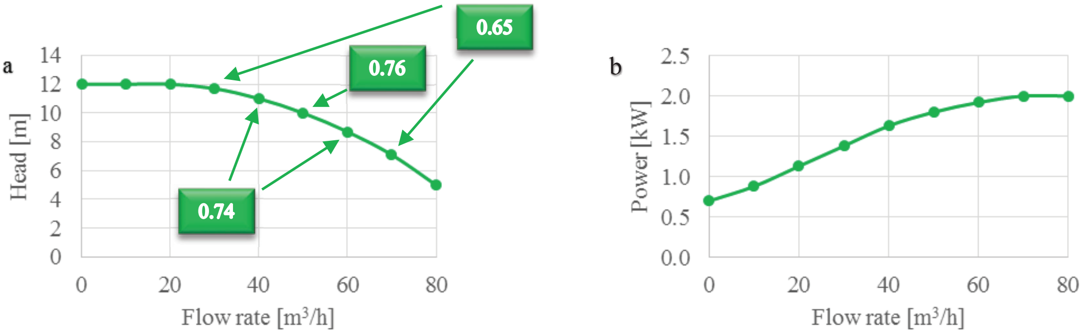


Fig. 4. (a) Characteristic curve of the selected pump; (b) Power curve of the selected pump

Table 4. Main characteristics of the pump

Flow rate value at the Best Efficiency Point (BEP)	50 m^3/h	Specific speed	0.57
Head at the Best Efficiency Point (BEP)	10 m	Diameter of the impeller	193 mm
Best efficiency value	0.76	Number of blades	7
Fixed rotating speed	1,450 rpm	Liquid processed	$H_2 0$ ($\rho \approx 1{,}000$ kg/m^3)

2.4. Non-dimensional analysis of PaT performance curves

Taking into account the selected pump, non-dimensional analysis was performed. Through non-dimensional analysis, it is possible to evaluate three coefficients related to main parameters that affect working conditions of the selected pump, namely flow coefficient (φ), head coefficient (ψ) and power coefficient (Λ). These three coefficients are independent from the physical dimension of the pump (diameter of the impeller) and its rotating speed, if the effect of the friction losses is considered as constant; in this way they can be used for evaluating other PaTs that work with the same fluid-dynamic conditions. Thus, results obtained using the selected pump in laboratory tests can be extended also to other pumps that work in similarity conditions.

3. Results and comments

3.1. The selected pump running in turbine mode: evaluation of the non-dimensional characteristic curve

Laboratory tests were carried out twirling the PaT at different rotating speeds: tests started from 450 rpm to 1,050 rpm, with steps of 200 rpm. By regulating the flow rate supplied at the inlet of the machine by means of a by-pass valve, the characteristic curve of the PaT running in turbine mode was obtained. After tests were performed, non-dimensional analysis of the machine was carried out. Graphs related to the relation between the specific speed and the non-dimensional power as well as the relation between the specific speed and the mechanical efficiency of the machine are shown in Fig. 5 taking into account different rotating speeds.

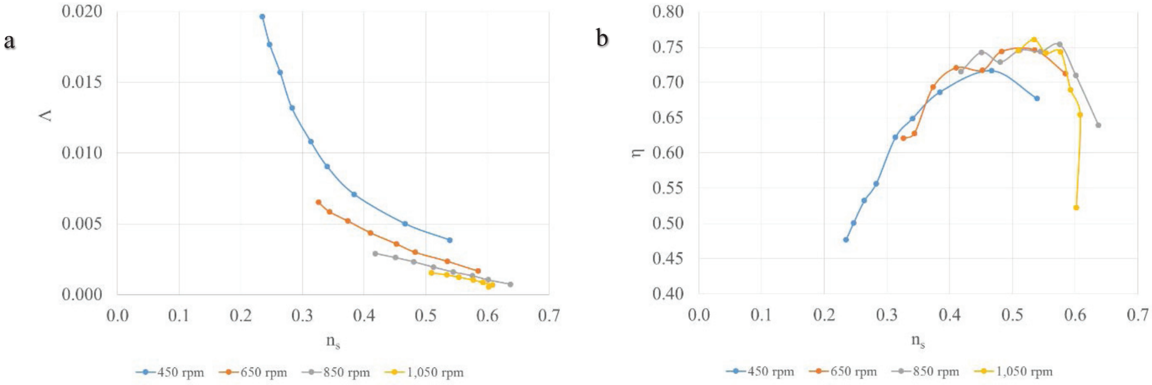


Fig. 5. (a) Specific speed – non-dimensional power; (b) Specific speed - mechanical efficiency

The non-dimensional characteristic curve of the PaT running in turbine mode, knowing its characteristic curve and the geometric dimension of the impeller, is shown in Fig. 6. In this figure, the highlighted point in the graph is the rated working point in which the machine operates at BEP.

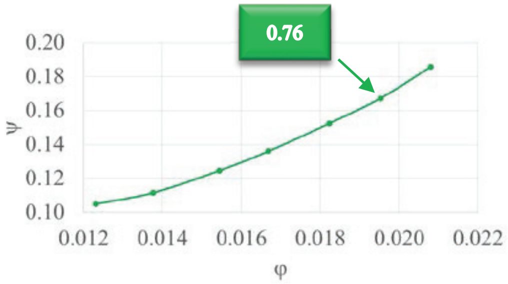


Fig. 6. Non-dimensional characteristic curve of the selected pump running in reverse mode

3.2. Real case study

Taking into account the hourly flow rate trend of Merano aqueduct shown in Fig.3 and the non-dimensional characteristic curve shown in Fig. 6, a PaT, working with the same fluid-dynamic conditions of the tested machine, was selected in order to exploit the highest amount of flow rates available from the aqueduct during the day. Being the available head of the aqueduct close to 60 m, Table 5 shows the main characteristics of the PaT, running at rated condition, which can be used in the branch of the investigated aqueduct.

Table 5. Main characteristics of the PaT running in turbine mode at BEP

Flow rate value at the Best Efficiency Point (BEP)	152 m^3/h
Head at the Best Efficiency Point (BEP)	60.88 m
Best efficiency value	0.76
Fixed rotating speed	2,900 rpm
Specific speed	0.57
Diameter of the impeller	0.19 m
Number of blades	7
Liquid processed	H_20 ($\rho \approx$1,000 kg/m^3)
Power	19.18 kW

Finally, the electrical energy produced in one day, taking into account the graph of the hourly flow rate trend of the Merano aqueduct and the power produced shown in Fig. 3 and Fig.7, respectively, is 338.11 kWh. This is the optimal result obtained considering that, from 1 to 5, the flow rate of the aqueduct will not be processed because they are smaller than the minimum flow rate processed by the PaT. In addition, in hours 8, 9, 20 and 21 not all the flow rate of the aqueduct will be processed because it is higher than the maximum flow rate processed by the PaT.

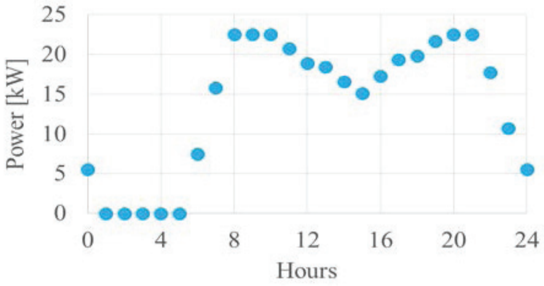


Fig. 7. Power produced by the PaT taking into account the hourly flow rate trend of the aqueduct

4. Conclusions

In this paper, a PaT was selected to perform laboratory tests in order to evaluate its performance in turbine mode and evaluate its potential use in energy recovery applications. A non-dimensional analysis was carried out and the characteristic curves of the PaT running in reverse mode were obtained. Results show that a maximum efficiency of 76% can be achieved in both direct and reverse mode at the same specific speed of 0.57. In addition, the BEP resulted to be close to the value evaluated using the McClaskey's theory rather than the other ones. Finally, a real case study was considered to evaluate the economic feasibility of installing a PaT, working with the same fluid-dynamic conditions of the tested PaT, in a part of the aqueduct of the city of Merano (BZ) that supplies water to 30% of the inhabitants. Results show that this PaT can achieve a rated power of 19.18 kW and an electric energy production of 338.11 kWh for each day of operation.

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