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Energy recovery in oil refineries through the installation of axial Pumps-as-Turbines (PaTs) in a wastewater sewer: a case study

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Abstract

This paper analyses an energy recovery solution for the application in an oil refinery, which has undergone significant changes in the last decades due to the construction of different plants, services, storage and logistics systems. Nowadays, with the aim to reduce the water contamination close to the refinery, the local regulations imposed to introduce solutions for the treatment of the groundwater underneath the oil treatment plants. In order to reclaim the site and to safeguard the areas close to the oil refinery, an intervention named "Pump & Treat" was adopted by an Italian company which consists in pumping up the underground water and treating it to remove any trace of polluting agent. Subsequently, a part of the treated water is discharged, by gravity, into the sea through a wastewater sewer. An Axial-Flow Pump (AFP) is studied in both pump and turbine modes for being installed in the wastewater sewer of the analysed oil refinery. After evaluating the availability of flow rate and head, the design characteristics of a proper axial turbine were identified. Computational Fluid Dynamics (CFD) simulations of an AFP are performed in both pump and turbine modes. The obtained results were used for scaling down the hydraulic machine and for defining a new one, properly adapted for the wastewater sewer, as energy recovery unit. The selected axial Pump-as-Turbine (PaT) allowed to achieve an economic saving of about 1706 €/year, leading to a Pay-Back Period (PBP) of about 1 year and 10 months.

Keywords: Axial-Flow pump; Pump-as-Turbine; Best Efficiency Point; Oil refinery; Energy saving

1. Introduction

Water is one of the most used clean resources that humans employ for producing electrical energy [1]. Initially, hydropower plants were limited only to the large-scale systems. These plants present two reservoirs: the upstream one is located at high altitudes where the water is collected, while the second one is placed downstream.

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The water flows inside a penstock from the upper reservoir to the lower one converting potential energy into kinetic one. Immediately upstream the lower reservoir, a hydraulic turbine is installed: its task is to convert the energy of the water into mechanical power by the rotation of the shaft on which it is assembled. However, most of the biggest available geodetic altitudes have been already exploited and, furthermore, the used technologies are almost mature. For this reason, in the last recent years other kinds of hydropower plants are taking the field with the name of small-scale hydropower. Generally, small-scale hydropower plants are located close to the rivers [2] or to the irrigation networks [3]. The advantages of these plants consist on supplying electrical energy to people that live in remote and rural zones [4]; at the same time, they are more cost-effective and they have a low environmental impact [5]. The hydraulic machines used in the small-scale hydropower sector are similar to the ones used in the large-scale hydropower sector, although they present some modifications. Among them, the most used machines are Agnew [6], Turgo [7] and Cross-flow [8]. Moreover, the application of the small-scale hydropower can be adopted also in other applications like Water Distribution Networks (WDNs) [9] and wastewater systems [10] for energy recovery purposes, thus reducing their energy consumption. Among the small-scale hydropower technologies, Pumps-as-Turbines (PaTs) are currently used in several cases as energy recovery solutions, especially in chemical plants like oil refineries where they are called Hydraulic Power Recovery Turbines (HPRTs) [11]. PaT is being a suitable choice due to its lower cost and easier use [12] with respect to hydraulic turbines, together with mass production, various standard sizes and easy availability of spare parts. On the contrary, PaTs should be used with flow rates close to the Best Efficiency Point (BEP) one or slightly higher, otherwise an efficiency drop at part-load conditions occurs. Considering oil refineries, besides HPRTs, also Axial-Flow Pumps (AFPs) can be used in reverse mode for energy recovery purposes in wastewater sewers. In this paper, an AFP provided in ANSYS® Workbench was studied in both pump and turbine modes by the means of Computational Fluid Dynamics (CFD) simulations to assess its performance and the technical and economic viability of the solution. Subsequently, similarity laws were used to scale down the machine to properly match the AFP operated as a turbine in the wastewater sewer of an oil refinery located in Italy for energy recovery purpose. Finally, the obtained economic saving is discussed.

2. Research and methods

2.1. CFD model

An Axial-Flow Pump (AFP), which was provided in ANSYS® Workbench, was used for performing CFD steady-state simulations in both pump and turbine modes. The studied AFP has 13 stator and 7 rotor blades. The working liquid is water at standard conditions (25 °C, 1 bar). The performance's curves in pump mode were obtained with a flow rates span of ±25% with respect to the BEP. In turbine mode, the characteristic curve was realized varying the flow rates up to ± 7.5% with respect to the BEP. Thanks to the rotational symmetry of the geometry and of the flow field, only one periodical blade channel of both stator and rotor was simulated. Table 1 lists the AFP's characteristics that mark out the performance of the studied hydraulic machine, while Fig. 1a and Fig. 1b show the fluid domain and the spatial discretization (stator and rotor blades plus the hub) of the one periodical blade channel, respectively.

Table 1. Main AFP's characteristics at BEP

Pump design	Axial	Hydraulic power [kW]	188.7	Hydraulic efficiency at BEP	85.0%
Number of stator and rotor blades	13-7	Rotating speed [rpm]	260	Impeller diameter [m]	1.09

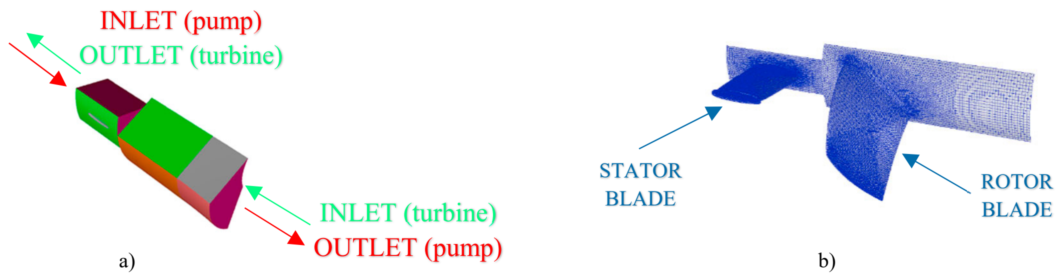


Fig. 1. Fluid domain (a) and the blades' mesh (b)

2.2. CFD set-up

The Boundary Conditions (BCs) used in the CFD model are shown in Table 2.

Table 2. Boundary Conditions (BCs) used

Type of boundary	BCs' values and conditions	Parameters
Inlet	Mass flow rate per vane [kg/s]	Intensity (fraction) = 0.0011 Length Scale [m] = 0.014
Outlet	Gauge Pressure: 0 [bar]	Backflow Intensity (fraction) = 0.1 Backflow Viscosity Ratio = 10
Wall	No-slip condition	-
Periodic	Rotational	-
Interface stator-rotor	Conservative Interface Flux Mixing Plane method	-

The presence of the other stator and rotor blades was taken into account by applying the periodic BC on the lateral faces of the analysed flow domain (Fig. 1a). Regarding the interaction between the rotating and the stationary domains, the Mixing Plane Model was used. Flow-field's data from adjacent zones are passed as BCs that are spatially averaged or "mixed" at the mixing plane interface. This approach removes any unsteadiness that would arise due to circumferential variations in the passage-to-passage flow field (e.g., wakes, shock waves, separated flow), thus yielding a steady-state result. The number of cells used for discretizing the fluid domain is equal to 1,172,532. Convective and diffusive terms of Reynolds Averaged Navier Stokes (RANS) equations are discretized with High-Resolution schemes. The turbulence is modelled by using the k-ω equations with an automatic wall function, which is commonly used for studying similar problems [12]. Simulations are stopped when a very low percentage variation is reached between the residuals of two successive iteration steps, with a normalized residuals drop lower than 10^{-6}.

3. Case study of the refinery's plant

3.1. Description of the water treatment plant

In this section, the treatment's plant of the refinery's wastewater is described and the available flow rate and head are discussed in order to correctly size the energy recovery unit equipped with the AFP. The wastewater is pumped from the underground and it is sent to the physical-chemical treatment plants. After the treatment, the water flows to a storage tank with a flow rate equal to 0.139 m^3/s; about 0.056 m^3/s is reused in other processes inside the oil refinery, while the remaining 0.083 m^3/s is discharged, by gravity, into the sea in compliance with the Italian legislation. The level of the water in the storage tank varies between +23 m to +18 m a.s.l., while the height of the sewer is fixed and located at +1.2 m a.s.l.. The sewer is constituted of a High-density Polyethylene (HDPE) PE100 pipeline (PN10, DN400) with an internal diameter of 352 mm. Fig. 2 shows: the height profile, expressed in meters, of the analysed site (brown line), the height profile of the sewer pipeline (blue line), the hydraulic profile of the pipeline taking into account the maximum water level (+23 m a.s.l.) and the lower one (+18 m a.s.l.) inside the storage tank (continuous green lines) and, finally, the hydraulic limit profile below which the discharge is no longer guaranteed for both the previous two cases (dotted green line). Therefore, in the worst case (water tank level of +18 m), the available hydraulic pressure at the sewer discharge is equal to 3.8 m: this datum was evaluated by subtracting the final pressure of the hydraulic profile (+15 m) with the final limit pressure of the hydraulic limit profile (+10 m) and the height of the sewer (+1.2 m). Therefore, a flow rate value of 0.083 m^3/s and the head of 3.8 m were used for designing the axial turbine.

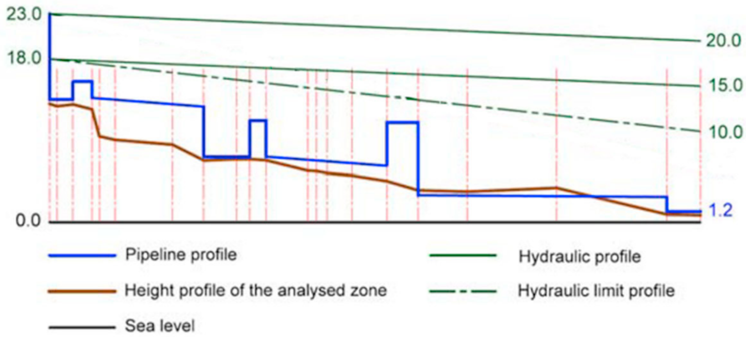


Fig. 2. Heights and hydraulic profiles, expressed in meters, related to the studied site

3.2. Sizing of the AFP using the similarity laws

Similarity laws allow to define the performance of hydraulic machines with different sizes provided that the fluid-dynamic similarity condition is met. The main parameters used in the similarity analysis are: the flow coefficient (Φ), the head coefficient (ψ) and the power coefficient (Λ) that can be evaluated with equations (1), (2) and (3), respectively.

$$\Phi = Q/(nD^3) \quad (1)$$
$$\Psi = gH/(nD)^2 \quad (2)$$
$$\Lambda = P/(\rho n^3 D^5) \quad (3)$$

After the CFD simulations were performed and the non-dimensional (N-D) parameters were calculated, the impeller diameter and the rotating speed of the scaled AFP were obtained by introducing in equations (1) and (2) the flow rate and the head values defined by the water treatment plant, equal to 0.083 m^3/s and 3.8 m, respectively.

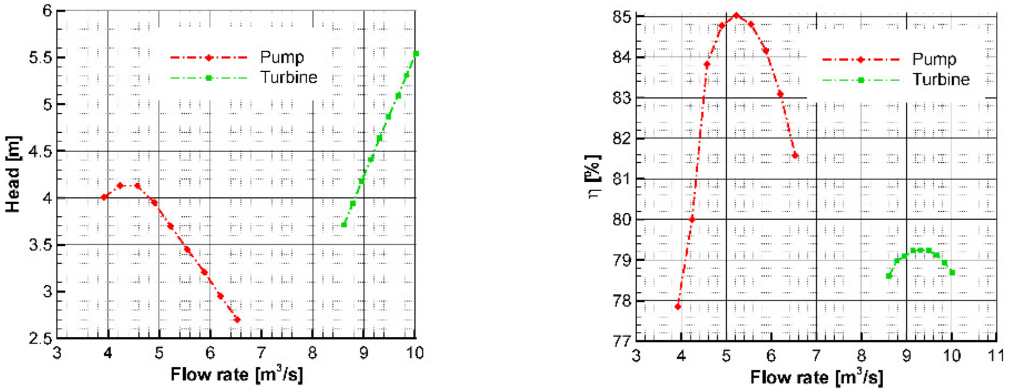
4. Results and comments

4.1. PaT's performance curves in both pump and turbine modes

Table 3 lists the BEP values of both operating modes obtained from CFD analysis of the AFP provided in ANSYS® Workbench. It is worth to notice that the BEP flow rate and head in turbine mode (9.31 m^3/s – 4.64 m) are higher than the ones in pump mode (5.22 m^3/s – 3.70 m) of about 78% and 25%, respectively, while the hydraulic efficiency, in turbine mode (79.3%) is lower than the one in pump mode (85.0%). In order to have a better view of the comparison between pump and turbine operation modes, Fig. 3 shows the characteristic and the efficiency curves of the simulated axial PaT. Thanks to the analysis of the non-dimensional parameters (based on the data reported in Table 3) and the dimensional data (reported in Fig. 3), the axial PaT that has to be installed in the wastewater sewer was designed. By imposing the head value of 3.8 m and the flow rate of 0.083 m^3/s in equations (1) and (2), the impeller diameter and the rotating speed obtained were equal to 0.108 m and 2364 rpm, respectively. Nevertheless, in order to obtain a perfect down-scaling factor of 1:10 with respect to the original machine design, the impeller diameter has been fixed to 0.109 m and, by using again equations (1) and (2) with D=0.109 m and Q =0.083 m^3/s, the head value and the rotating speed were found to be equal to about 3.66 m and 2310 rpm, respectively. It is worth to notice that the impeller diameter of 0.109 m is lower than the diameter of the pipelines located in the installation site, therefore a specific section reduction piece should be considered in the hydraulic circuit. Table 4 lists the main geometrical and performance characteristics of the axial PaT designed for this test case, while Figure 4 shows the characteristic and the efficiency curves of the scaled PaT in both pump and turbine modes, respectively.

Table 3. BEP values of the simulated axial PaT in both pump and turbine modes at 260 rpm

MAGNITUDE (BEP)	PUMP MODE	TURBINE MODE
Flow rate [m^3/s]	5.22	9.31
Head [m]	3.70	4.64
Hydraulic efficiency (%)	85.03	79.25
Hydraulic power [kW]	188.69	422.07
Impeller diameter [m]	1.09	1.09

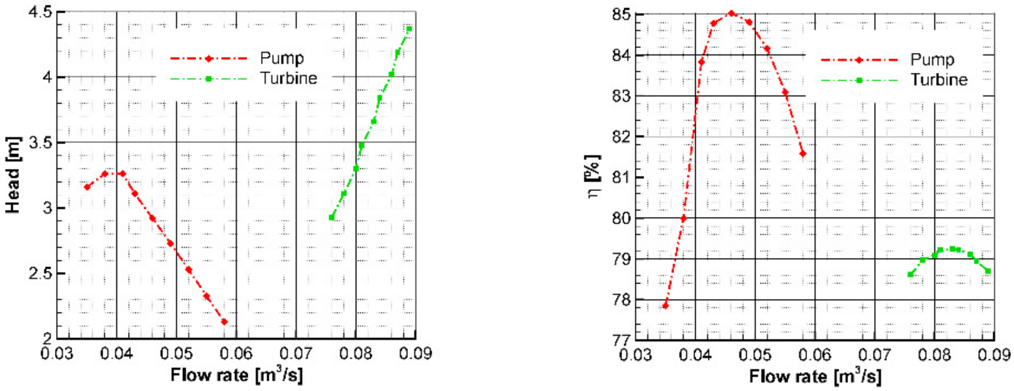


a) b)

Fig. 3. Characteristic and efficiency curves of the simulated axial PaT in both pump and turbine modes at 260 rpm

Table 4. BEP values of the designed axial PaT in both pump and turbine modes at 2310 rpm

MAGNITUDE (BEP)	PUMP MODE	TURBINE MODE
Flow rate [m^3/s]	0.046	0.083
Head [m]	2.92	3.66
Hydraulic efficiency (%)	85.03	79.25
Hydraulic power [kW]	1.32	2.96
Impeller diameter [m]	0.109	0.109



a) b)

Fig. 4. Characteristic and efficiency curves of the designed axial PaT in both pump and turbine modes at 2310 rpm

4.2. Energy and economic analysis

Once the main performance of the axial PaT were evaluated, the installation of the designed PaT, on both energy and economic points of views, will be discussed. The PaT is chosen considering a fixed rotating speed of 2310 rpm, thus a gear box or a mechanical speed reduction system should be introduced to match the speed of the electric generator. Finally, considering the magnitudes of the designed axial PaT listed in Table 4 and a fixed mechanical efficiency equal to 95% for considering the friction losses, a mechanical power of 2.23 kW can be produced. The plant operates continuously for about 8500 h/year: thus, it recovers 18,955 kWh and, being the electricity price for the oil refinery equal to 0.09 €/kWh, as suggested by the plant's managers, an economic saving of about 1706 €/year is achieved. The cost of the overall investment is calculated taking into account the costs of the axial PaT, the electrical power board and inverter, both mechanical and electrical assembly, and assuming a maintenance cost equal to 10% of the sum of the previous mentioned items' costs. The cost items, the net economic savings and the PBP are listed in Table 5.

Table 5. Net economic savings and PBPs of the investments

Cost item	Value
Axial PaT [€]	850
Electrical power board and inverter [€]	500
Mechanical and electric assembly [€]	1262
Maintenance [€/year]	261
Economic saving [€/year]	1706
Net economic saving (Economic saving – Maintenance) [€/year]	1445
PBP	~ 1 year and 10 months

5. Conclusions

This work highlights the unexploited potential of considering small-scale hydropower units for energy recovery applications in industrial processes, like the one presented in this case study. CFD steady-state simulations of an AFP operating in both pump and turbine modes were carried out. Results showed that the BEP flow rate and head in turbine mode (9.31 m^3/s – 4.64 m) are higher than the ones in pump mode (5.22 m^3/s – 3.70 m) of about 78% and 25%, respectively, while the hydraulic efficiency in turbine mode (79.3%) is lower than the one in pump mode (85.0%). Similarity laws were used for scaling the machine to define a proper axial PaT to be used in a wastewater sewer of an oil refinery. The design flow rate of the installation site is equal to 0.083 m^3/s and, taking into account the worst hydraulic profile along the pipe, a minimum hydraulic pressure of 3.8 m is available. The axial PaT can exploit an head of about 3.66 m, leading to a power production of 2.23 kW. In this case, considering 8500 h/year of the oil refinery operating hours, an yearly energy recovery of 18,955 kWh was achieved and, with an electricity price of 0.09 €/kWh, an economic saving of 1706 €/year was obtained. Finally, considering an overall capital cost of 2612 € and a maintenance cost of 261 €/year, a PBP of about 1 year and 10 months can be achieved.

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