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New design solutions for low-power energy production in water pipe systems

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Abstract: This study is the result of ongoing research for a European Union 7th Framework Program Project regarding energy converters for very low heads, and aims to analyze optimization of new cost-effective hydraulic turbine designs for possible implementation in water supply systems (WSSs) or in other pressurized water pipe infrastructures, such as irrigation, wastewater, or drainage systems. A new methodology is presented based on a theoretical, technical and economic analysis. Viability studies focused on small power values for different pipe systems were investigated. Detailed analyses of alternative typical volumetric energy converters were conducted on the basis of mathematical and physical fundamentals as well as computational fluid dynamics (CFD) associated with the interaction between the flow conditions and the system operation. Important constraints (e.g., size, stability, efficiency, and continuous steady flow conditions) can be identified and a search for alternative rotary volumetric converters is being conducted. As promising cost-effective solutions for the coming years, adapted rotor-dynamic turbomachines and non-conventional axial propeller devices were analyzed based on the basic principles of pumps operating as turbines, as well as through an extensive comparison between simulations and experimental tests.

Key words: *energy converter; low-power energy; water pipe system; computational fluid dynamics (CFD); lab tests*

1 Introduction

The goals of this study were to perform viability analysis and design solutions hydraulically optimized for small turbines, with a particular focus on the simplicity of manufacture. As an economical renewable energy with negligible environmental impacts, micro hydropower will play an important role in future energy supplies, allowing decentralized solutions, particularly for developing regions and countries. It is an alternative solution to diesel generators in rural or remote areas. Schemes with a power output less than 100 kW are usually referred to as micro hydro schemes. For a power output less than 5 kW, there are several cost-effective ways for small rivers or water supply system (WSSs) to

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generate electricity in remote communities. The cost of the necessary micro hydro equipment per unit of energy is lower than that of diesel generators, wind turbines, or photovoltaic systems, especially when the equipment is locally manufactured.

The challenge is therefore to provide engineering designs and implementation methods that can be effectively customized for a wide range of schemes, particularly in the region of low flow rates, WSSs, wastewater irrigation schemes, and possible energy recovery projects, despite the fact that less attention is paid to low-power turbine technology. Small-head axial-flow hydro turbines have long been the best solution. The optimization of these turbines has enabled the modern axial-flow hydro turbines to reach operating efficiencies of over 90%. However, micro hydro turbines in the range of 100 W to 20 kW have been the mainstay of researchers and industry of late, thus making them an open and exciting area of study.

The design and behavior of micro hydro turbines cannot be based on an exact scaling down of large turbines due to associated scale effects. Research on new cost-effective micro hydro solutions is insufficient and has been carried out by a few concerned individuals mainly focusing on application in developing countries.

2 Volumetric and rotor-dynamic hydromachines

The transfer of mechanical energy from the flow to a shaft in rotation can be accomplished by (1) volumetric machines, such as rotational movement of positive displacement (PD) machines, or by (2) rotor-dynamic machines. Using the operating principles of PD pumps and centrifugal pumps, respectively, as baselines for volumetric and rotor-dynamic turbomachines, a significant difference can be seen in the pumps' response to the system's head/flow curve. PD pumps can improve efficiency while lowering costs. They are based on the same principle, which consists of filling a space with a volume of water and then transferring it. The capacity remains constant with various discharge pressures. This allows for a high degree of system control. PD pumps create flow and centrifugal pumps create pressure (Parker 1994). Viscous sensitive fluids may require PD pumps so as to avoid the high shearing action of centrifugal impellers. Centrifugal pumps are usually not applied to liquids with high viscosities, due to the rapid loss of efficiency with the increase of viscosity values.

In volumetric machinery, the flow is confined to one or more compartments of variable size. The change in volume can be achieved through a movement of alternative translation or rotation and the compartments can remain at a fixed position or move up along the machine. In rotor-dynamic machines, power is transferred through a runner with blades and the flow around the blades. When the available head is small, a high discharge is necessary for the generation of minimally adequate power. Fig. 1 shows the typical classification of pumps. As a kind of PD pump, rotary pumps operate in a circular motion and maintain a quasi-constant discharge volume with each revolution of the pump shaft. The same volume of liquid remains within the pump until the pump's volume is reduced and the liquid is forced out. These pumps work well with a wide range of viscosities.

Fig. 2 shows performance curves for a centrifugal pump and the operating point obtained from the intersection of the system curve (with the head losses as a function of discharge value) with the pump curve, where H is the head, P is the power, η is the efficiency, Q is the discharge, and Q_{bep} and H_{bep} are the discharge and the head, respectively, for the best efficiency.

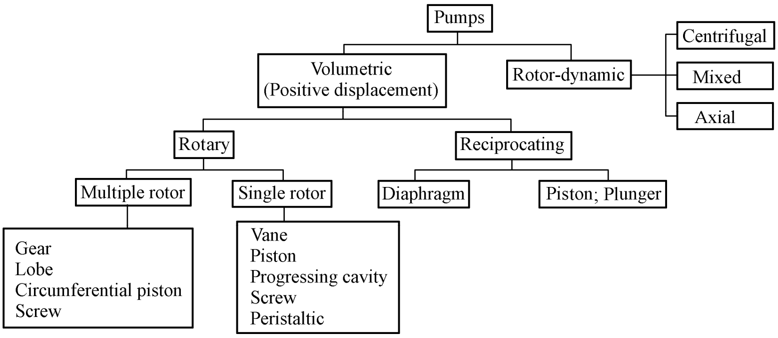

Fig. 1 Typical classification of pumps

Centrifugal pumps differ from rotary pumps in that they rely on kinetic energy rather than mechanical means to move liquid. Liquid is forced out of the pump by the energy obtained from the rotating impeller.

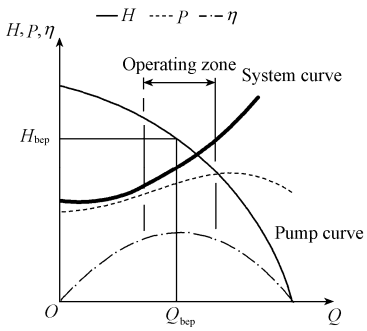

Fig. 2 Performance curves for a centrifugal pump

In a comparison analysis between rotary and centrifugal pumps, the following is apparent: (1) rotary pumps are more suitable for fluids with higher viscosity; (2) rotary pumps accept maximum discharges of 208 L/s, while centrifugal pumps accept maximum discharges of 7 600 L/s; (3) rotary pumps generally have a higher efficiency and lower energy costs; (4) rotary pumps offer better flow control; and (5) both machine types have equivalent life-cycle costs. The choice of a centrifugal or a PD pump is not always a clear one, but comprehension of the behavior of each type of machine is essential (Rodger 2007) (see an application in Fig. 3).

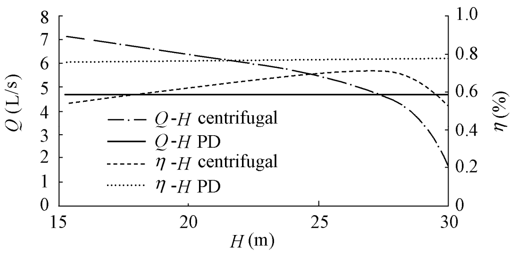

Fig. 3 Flow rate and efficiency vs. pressure for centrifugal and PD pumps

Flow varies with head for a centrifugal pump, but is more or less constant with pressure variation for a PD pump. Pressure changes have little influence on efficiency for PD pumps but a significant influence for centrifugal pumps.

3 Low-cost solutions

3.1 Viability analysis

These hydro-machines are focused on small power values since, for higher power values, different turbines suitable for different system characteristics are available on the market. There are possible solutions for low-power hydro-machines that are not always available on the market, such as conventional water turbines, pumps operating as turbines (i.e., pumps operating in reverse mode, referred to herein as PAT), and even new converters.

Higher efficiencies and longer payback periods lead to higher investment costs. From Fig. 4, we can find that most of the points obtained are above the water turbine curves, except for some points with power values below roughly 10 kW, when the payback period (S) is six years (i.e., non cost-effective situations).

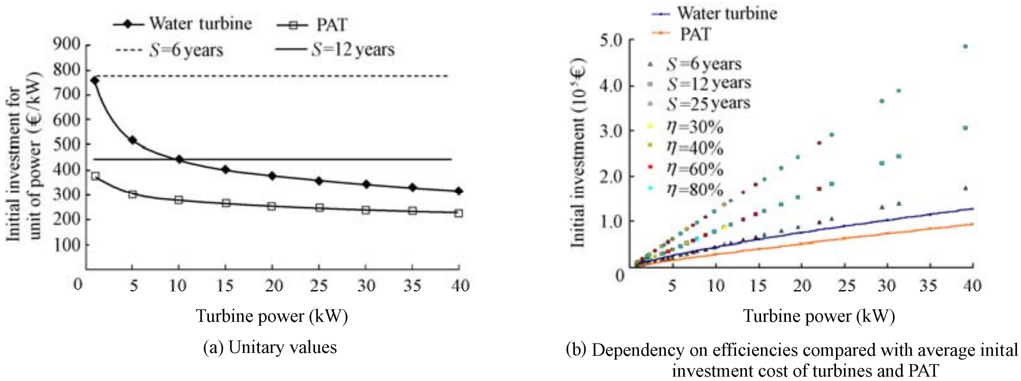

Fig. 4 Investment costs in low-power machines for different expected payback periods

Due to the large existing market for water pumps, they tend to be less expensive than conventional water turbines (Fig. 4). In this analysis, the operational and maintenance costs were not taken into account since these costs have less significance than the investment cost. Fig. 4(b) shows that the cost effectiveness of the system decreases with shorter payback periods. For a payback period of six years, when compared with a conventional water turbine, the system is only economically cost effective for a power output above 10 kW. With increasing power output, higher initial investments are permitted, since the amount of energy produced and sold to the grid is higher, increasing the project's profits. An increasing trend of cost effectiveness with the increase of payback periods with varying H, Q, and efficiency is shown in Fig. 5, in which the efficiencies 30%, 40%, 60%, and 80% correspond to the flow intervals Q_1, Q_2, Q_3, and Q_4, respectively.

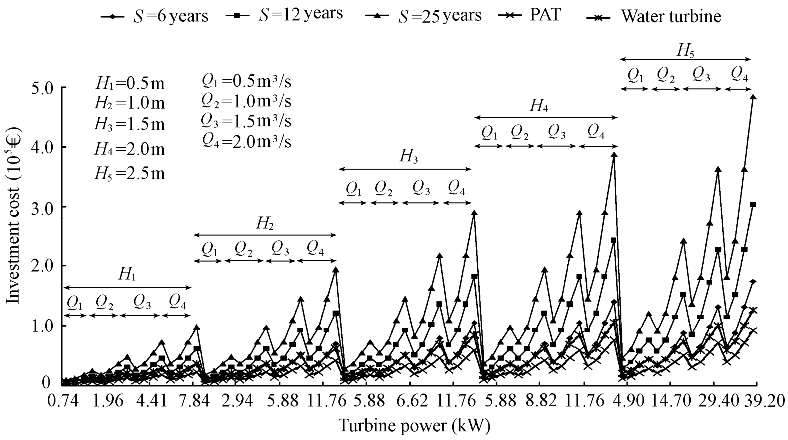

Fig. 5 Investment cost vs. turbine power with varying H and Q for different payback periods

3.2 Design conception

3.2.1 Volumetric converters

When a piston moves with a translation movement inside a cylinder, the velocity of the piston movement varies periodically between zero at the extremes of the course and a maximum value (positive or negative) at an intermediate point. Since the flow is proportional to the speed of the piston, it is impossible to feed a simple cylinder with a constant flow.

The transfer of energy from the translation movement of a piston into a rotational shaft of a generator can be made through the mechanism known as the rod and handle, represented in Fig. 6.

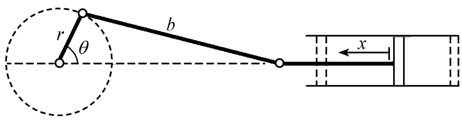

Fig. 6 Scheme of a piston

Designating b and r, respectively, as the lengths of the rod and handle ($b > r$), and considering the x-origin the midpoint between the extremes of movement of the piston, the position of the piston in the x-direction depends on the angle θ:

$$x = b - r\cos\theta - \sqrt{b^2 - r^2\sin^2\theta} \tag{1}$$

If the axis of the handle, connected to the shaft of the generator, rotates with a constant angular velocity ω, and $\theta = \omega t$, then

$$x = b - r\cos(\omega t) - \sqrt{b^2 - r^2\sin^2(\omega t)} \tag{2}$$

Using the derivative with respect to t, the velocity of the piston movement can be obtained:

$$v = \frac{\mathrm{d}x}{\mathrm{d}t} = \omega\, r \sin(\omega t)\left[\frac{\cos(\omega t)}{\sqrt{\dfrac{b^2}{r^2} - \sin^2(\omega t)}} + 1\right] \tag{3}$$

The acceleration is

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \omega^2 r \left[\cos(\omega t) + \frac{\frac{b^2}{r^2}\cos(2\omega t) + \sin^2(\omega t)}{\left(\frac{b^2}{r^2} - \sin^2(\omega t)\right)^{3/2}} \right] \tag{4}$$

If the friction and inertia of moving parts are negligible, the torque on the handle from an axial force F_{p} applied on the piston and oriented in the positive direction of x will be

$$M = F_{\mathrm{p}}\ r \sin(\omega t) \left[\frac{\cos(\omega t)}{\sqrt{\frac{b^2}{r^2} - \sin^2(\omega t)}} + 1 \right] \tag{5}$$

Comparing this equation with the piston velocity, it is verified that $M/F_{\mathrm{p}} = v/\omega$. The validity of this formulation is evident since the power provided by the flow to the piston (P= $F_{\mathrm{p}}xv$) has to be equal to the power transmitted by the handle to its shaft ($P = Mx\omega$).

The elimination of points of zero torque can only be achieved by using two cylinders with double inlets installed in each cylinder and with a phase lag of 90º between pistons during the operation, or by using three cylinders with a simple inlet installed in each cylinder and with a phase lag of 120º between pistons during the operation (Fig. 7). It was also verified that the level of flow regulation and torque significantly depends on the length of the rod compared to the handle, with advantages in using as long a rod as possible and reducing the length of the handle. Other problems are the size, turbulence, and vibrations of these machines.

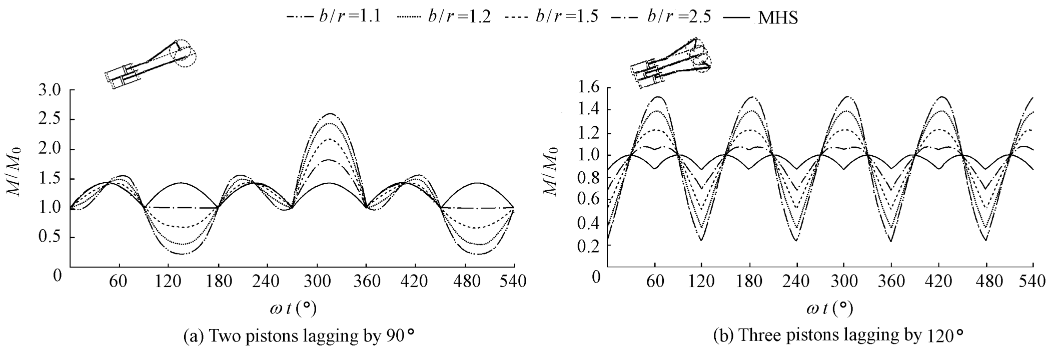

Fig. 7 Variation of torque in two and three pistons lagging by 90º and 120º in operation, respectively (M_0 is the ideal rated torque; MHS means simple harmonic movement for $b/r = \infty$)

A specific analysis was conducted of the discharge variability ($\varepsilon = (Q_{\max} - Q_{\min})/Q_{\mathrm{med}}$) of different volumetric machines presented in Table 1. Based on analysis of the discharge variability of rotary volumetric machines and PD energy converters, this study was performed in order to create a new energy converter inspired by a Wankel motor, which seems to be the best volumetric turbine with lesser discharge variability for WSSs. The fluid (water) is quasi-incompressible and quasi steady state flow conditions (with almost constant discharge) are imposed in the trunk of main pipes of the WSS. The size of volumetric machines for very small heads is an important factor in the final decision (and consequently its influence on the viability analyses).

Table 1 Discharge variability for different volumetric machines

Volumetric machine	Discharge variability (%)	
	MHS	b/r = 2.5
One simple inlet piston[1)]	314	339
One double inlet piston[2)]	157	169
Two simple inlet pistons[1)] (180º)	157	169
Two double inlet pistons[2)] (90º)	33	33
Three simple inlet pistons[1)] (120º)	14	42
Lobular type	24	
New PD turbine type (inspired by Wankel motor)	<11	

Note: The degrees in brackets are the phase lag of pistons during their operation; [1)] An inlet and outlet pair is at the top of a cylinder; [2)]An inlet and outlet pair is at the top and another pair is at the bottom of each cylinder.

3.2.2 Rotor-dynamic turbomachines

Some researchers have become interested in PATs for many types of small applications. Many techniques have been developed to date, including those of Sharma (1985), and, more recently, Williams (1992), Alatorre-Frenk (1994), Ramos and Borga (1999, 2000), Valadas and Ramos (2003), Singh et al. (2004), and Singh (2001, 2005).

In recent years, micro hydro development has become a possible new application area for PATs, where they are used to replace the expensive turbine units. These are often decentralized energy systems with capacities below 100 kW. Due to the huge market for pumps of all possible sizes, they are widely available, cheap, and suitable machines. They also have many advantages over custom-made turbines with respect to the maintenance. Due to the fixed geometric conditions of the flow within the pump casing and impeller, PATs have poor part-load performance. This is one of most challenging problems for micro hydro systems based on PATs. A PAT is very sensitive to changing boundary parameters, namely head and discharge (Table 2). Hence, inappropriate pump selection will result in a shift of the operating point (low values of percentage of load-power in Table 2), delivering an undesired output, and perhaps ultimately causing the failure of the project.

Table 2 Main characteristic parameters of PAT

Rotational speed of pump (r/min)	Percentage of load-power (%)	Power (kW)	H (m)	Q (L/s)	η_t (%)	η_G (%)	$\eta_t\eta_G$ (%)
39.7	100	22.8	30.3	92.0	83.4	86.0	71.7
	80	18.2	26.8	84.0	73.1	84.0	61.4
	60	13.7	23.2	75.0	61.4	83.5	51.2
94.4	100	9.7	10.4	115.0	82.7	86.0	71.1
	80	7.8	8.9	106.8	71.2	84.0	59.8
	60	5.8	7.4	97.0	58.8	83.5	49.1

Note: η_t is the efficiency of the turbine; η_G is the efficiency of the generator.

The main parameters under analysis were converted into dimensionless parameters, such as discharge number $\varphi = Q\big/\left(ND^3\right)$, with the discharge Q in m^3/s, rotational speed N in r/s, and the runner diameter D in m; and head number $\psi = gH/\left(N^2D^2\right)$, with net head H in m, N in r/s, and D in m. Fig. 8 shows head number (ψ) and discharge number (φ) curves, from lower to higher specific speeds. The lower specific speed ψ-φ curves also have steeper slopes when compared to the upper specific speeds. Each PAT has a different maximum operating efficiency, which is also related to the size of the machine and the scaled hydraulics within it. The head corresponding to each maximum operating efficiency decreases with the increase of the discharge as the rotational speed is increased (see the best efficiency point (BEP) trend line, and the intersection of this line with the ψ-φ curves).

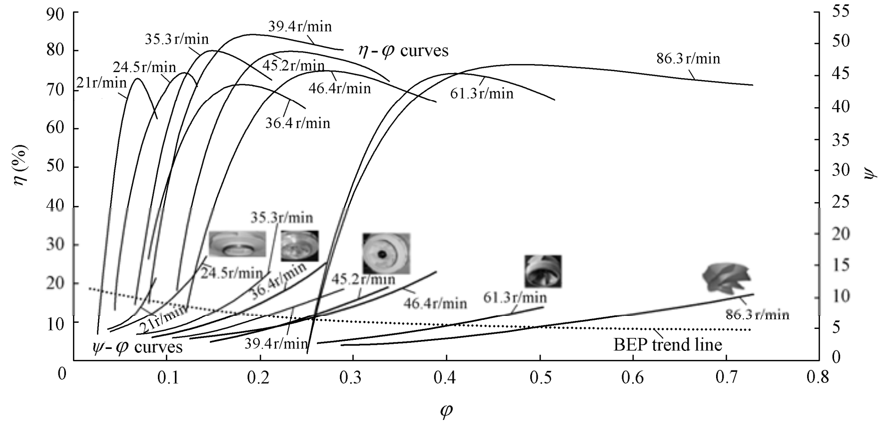

Fig. 8 Performance curves of radial flow PATs (Singh 2005; Rawal and Kshirsagar 2007)

There have been recent investigations of new axial propeller turbines specifically suited to very low heads. APRL (2001) has marketed propeller turbines that produce 200 W-1000 W of power with low operating efficiencies between 35% and 50%. Demetriades (1997) and Upadhyay (2004) designed propellers for turbines that produce less than 1 kW of power. Simpson and Williams (2006) developed a 5-kW propeller turbine for 3-4 m of head, with an efficiency of 65%. Alexander et al. (2009) developed propeller runner models for 3-9 m of head and 1.5-3 kW of power, which have peak efficiencies in the range of 68% to 74%. Most of the work in micro propeller turbines has not been widely disseminated, showing a greater need for optimization studies using both experimental and computational tools (Singh and Nestmann 2009).

The aim of this paper is to present initial developments of new hydraulically suitable energy converters (different types of runners) for micro hydro application that can be easily manufactured and installed in remote regions. Energy recovery could be another area of application of these small turbine units in small rivers, water supply and drainage systems, or even irrigation canals where the output power is too small for a conventional turbine to be used.

4 CFD analysis

4.1 Brief description

Computational fluid dynamics models (CFDs) are important tools for validating the experimental results. They make different turbine runners and flow conditions more understandable. The use of CFDs requires more sensitive and detailed analysis of the interaction between the flow and the boundary for different flow conditions using experimental tools associated with the real set-up limitations. Researchers and manufacturers use these advanced models to design new products and for specific analyses of flow behavior.

The flow within any energy converter, in particular a rotary PD turbine, propeller, or PAT, is known to be very complex. The objective of the simulation is to obtain results as close as possible to the experimental data. In these devices, the turbulence consisting of fluctuations varying with time and space in the flow field can have a significant effect on the machine behavior. Turbulence models are normally used to predict these effects on the flow pattern. The well-known turbulence model that is commonly used is the k-ε model. It is considered an industry standard that offers accurate results (Rawal and Kshirsagar 2007). It has proven to be stable and numerically robust, and has a well-established mode suitable to predicting the dynamic behavior of hydromechanical devices or of limited flow zones. For this purpose, it is necessary to create suitable meshes for full flow characteristics modeling. After generating the mesh and considering the geometrical characteristics of devices, the CFD provides simulation results based on initial data and flow conditions.

4.2 Simulation result analysis

This study deals with four innovative solutions to the energy problems related to a pressurized integrated solution for WSSs or for rivers with low flow rates and small heads. These solutions can provide a cost-effective alternative to actual turbines and are especially appropriate for micro hydropower generation, due to their simplicity in design.

A new rotary PD energy converter, an open mixed-flow PAT, and two simple propellers are devices that can operate as new turbines using either volumetric or changing flow, imposing rotation on an impeller and suggesting a high potential for these possible future power converters in the present energy scenario, which must be improved.

The numerical simulations aid the investigation of different types of configurations and parameters that cannot (or not easily) be obtained or measured experimentally. An appropriate mesh size was chosen (Fig. 9).

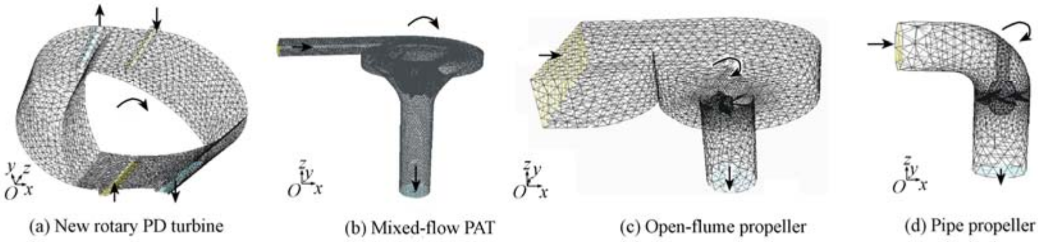

Fig. 9 Computational meshes

The flow patterns are shown in Fig. 10. For the new rotary PD turbine, the flow passes around the rotor in a similar manner through both the inlet and outlet (Fig. 10 (a)). For the mixed or diagonal flow runner PAT and the simpler propeller runner, the flow is seen to be entering from the volute casing, passing through the impeller rapidly since it is influenced by the impeller rotation, and flowing into the draft tube with a bit swirling (Figs.10 (b), (c), and (d)).

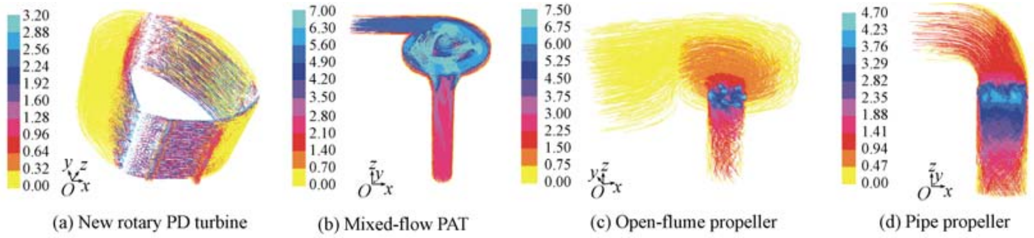

Fig. 10 Pathlines by velocity magnitude (Unit: m/s)

The quantitative results are expressed in terms of turbulence intensity (Fig. 11), total relative pressure variation across each turbine (Fig. 12), and wall shear-stress along the turbines (Fig. 13).

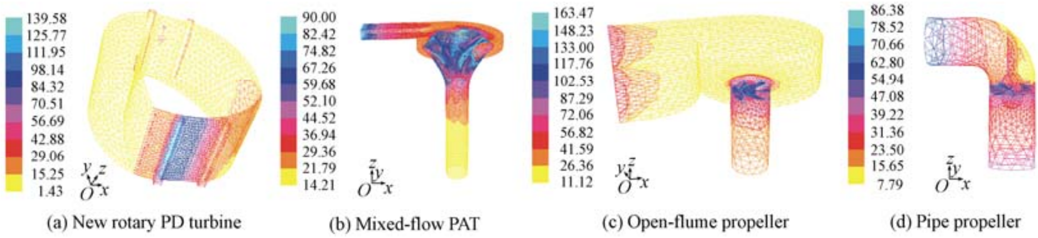

Fig. 11 Contours of turbulence intensity (Unit: %)

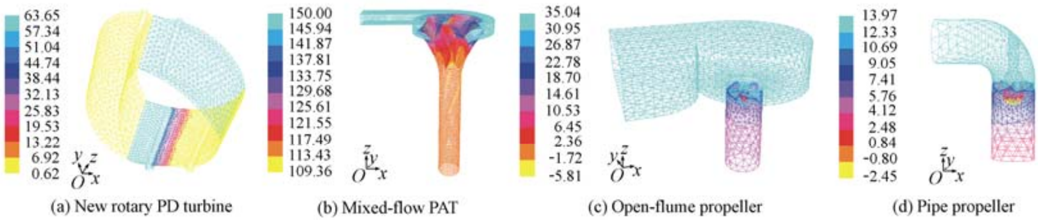

Fig. 12 Contours of total pressure (Unit: kPa)

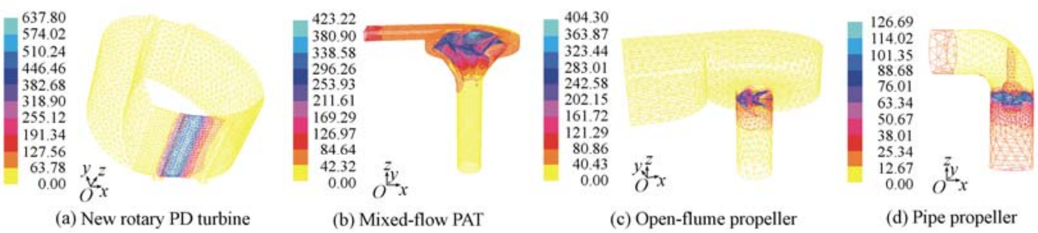

Fig. 13 Contours of wall shear-stress variation (Unit: Pa)

These simulations allow identification of critical zones that affect turbine efficiency and consequently the mechanical power transmitted to a generator.

The numerical simulation was restricted to hydraulic studies and hence some of the specific features were not modeled, such as bearings, bushings, and leakage in seals. However, the results are very useful, showing an effective prediction for new developments and applications. Fig. 14 presents a sequence of graphs with increasing discharge and head numbers covering a large range of applications. In order to analyze the behavior of several turbines under different hydraulic conditions, some comparisons between lab tests and CFD simulations were performed. The results presented are promising values (with BEP between 80% to 90%), but must be tested with experiments. During this extensive lab work, some turbines were tested under non-ideal conditions due to the limitations in the discharge available, which also conditioned the head and the runner speed.

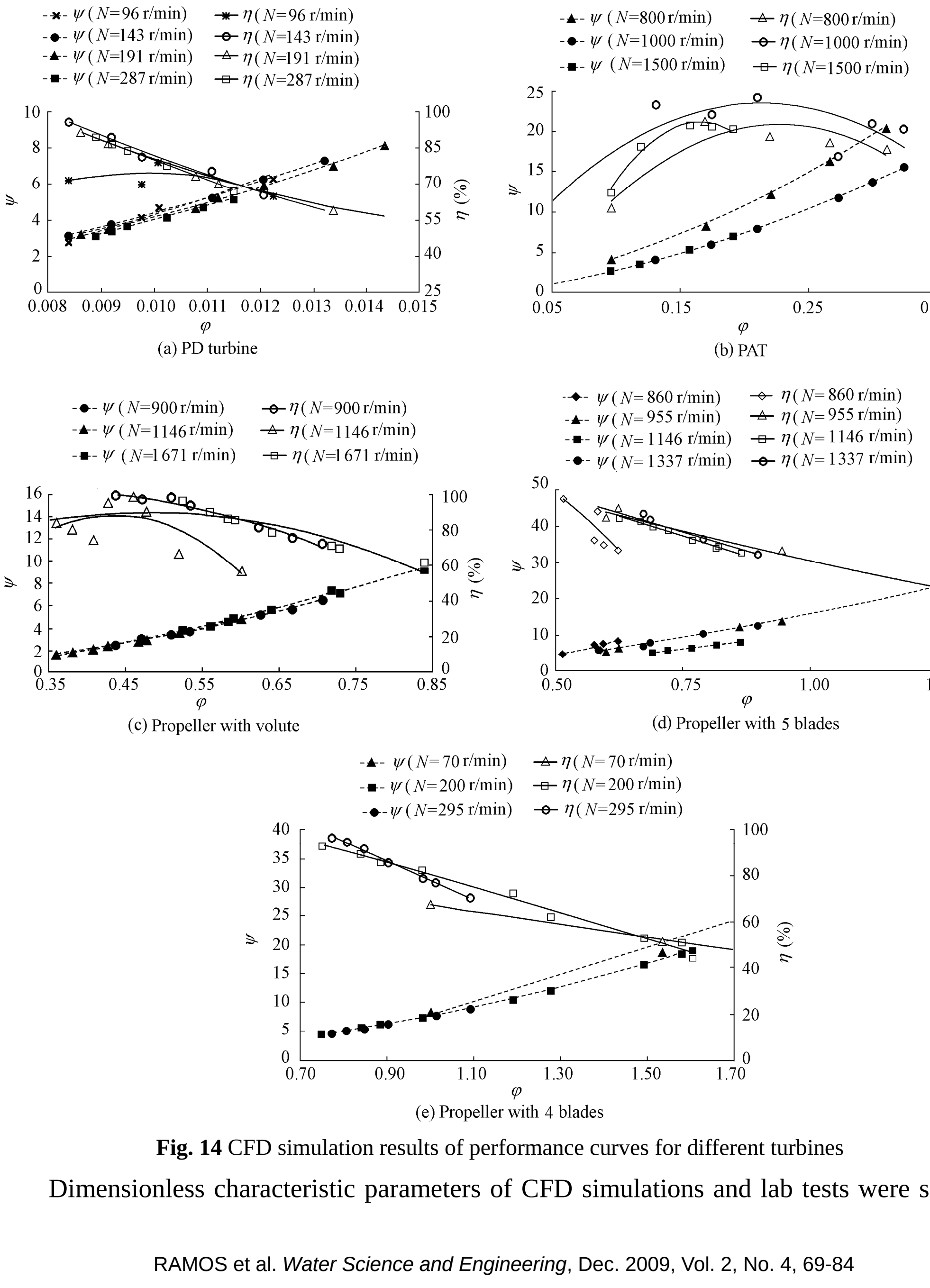

Fig. 14 CFD simulation results of performance curves for different turbines

Dimensionless characteristic parameters of CFD simulations and lab tests were selected and compared as shown in Fig. 15, in which H_0 and Q_0 are the rated values. A comparison of CFD simulations of the different turbines as well as their comparison with some lab tests shows typical trends and a good fit in the performance behavior.

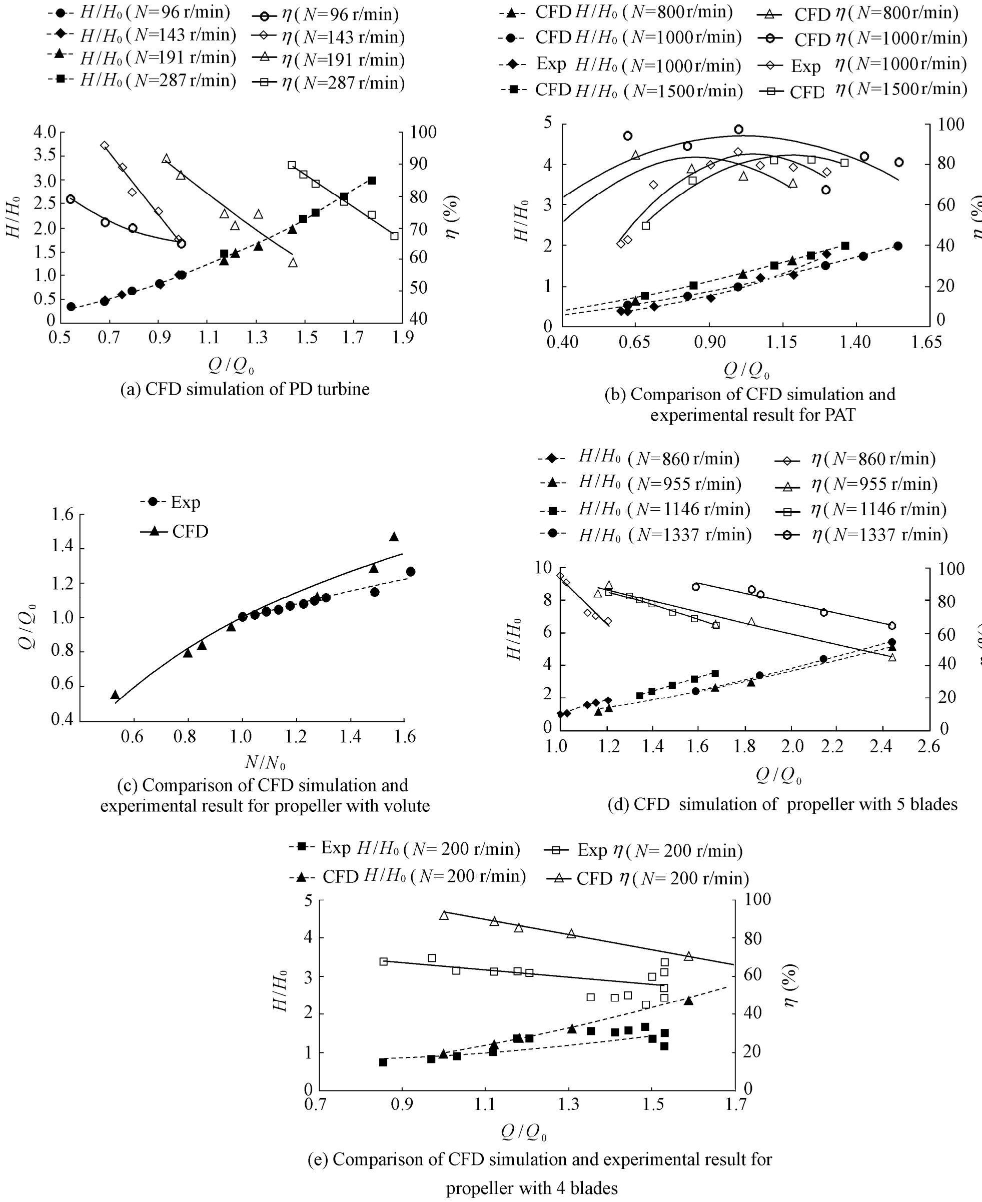

Fig. 15 CFD simulations and experimental results of dimensionless characteristic parameters for different turbines

Table 3 shows the characteristics of typical converters developed with the main objective of providing the small power outputs normally available in most pressurized pipe systems, such as WSSs, irrigation systems, or other types of drainage systems. The geometry of different turbine types is shown in Fig. 16.

Table 3 Characteristics of new energy converters

Turbine	D (mm)	H_0 (m)	Q_0 (m^3/s)	N_0 (r/min)	η_{max} (%)	P_{mec} (W)	Range of application		
							Q (10^{-3} m^3/s)	H (m)	N (r/min)
PD turbine		3.00	0.021	191	87	533	12-65	>1	80-600
PAT	236	11.4	0.044	100	97	4 911	<50	6-20	800-1 500
Propeller with volute	200	3.00	0.056	1 000	98	1 340	40-95	1-8	500-1 400
Propeller with 5 blades without volute	100	2.86	0.013	1 337	97	351	6-15	0.6-4	600-1 400
	200	8.77	0.092	1 146	97	7 660	70-150	5-20	900-1 400
Propeller with 4 blades without volute	100	0.12	0.004	300	95	4	3-5	0.05-0.25[1)]	200-300
	200	1.00	0.033	300	85	139	9-45	0.05-1.0[1)]	70-300
	200	5.32	0.109	1 000	97	5 510	110-200	5-18	900-1 400

Note: N_0 is the runner speed for rated conditions; P_{mec} is the mechanical power; [1)] The data are obtained from available lab conditions.

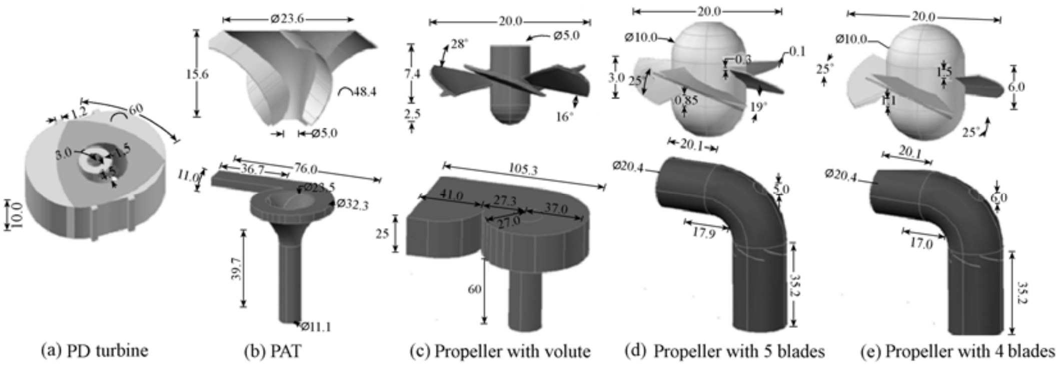

Fig. 16 Geometry for different turbines (Unit: 10 mm)

This shows a large range of possible applications that the traditional turbines do not cover adequately in a cost-effective manner. These machines are cheap, quite simple, and normally composed of only a runner, without any guide vane. Consequently, they are appropriate for operation under almost constant-flow conditions, such as typically occurring in the trunk of main water supply pipes or at least in systems equipped with a discharge control valve.

5 Applications

It is possible to save around 20% of the energy consumption by increasing energy efficiency on a cost-effective basis in WSSs. Most of the significant small hydropower stations rely on natural hydrological regimes, which have seasonal fluctuations of significant amplitude. WSSs are, in the majority of cases, large consumers of energy and represent a significant portion of the expenses of a water company. So the solutions presented in this work can help improve the energy and water management policies, preserve water resources, control the energy consumption, and protect the environment, which are priorities for this new era in which water and energy concerns are analyzed together.

Water consumption requires the utilization of energy sources. Fig. 17 shows a typical water consumption pattern of Portugal for one day (24 hours) that is quite similar to an energy load consumption pattern. In Fig. 17, the load factor is Q/Q_{mean} and consumption+pump means the sum of energy consumed and stored in pumps during the night. Based on this fact, a joint solution that considers both the consumption of water and energy must be found.

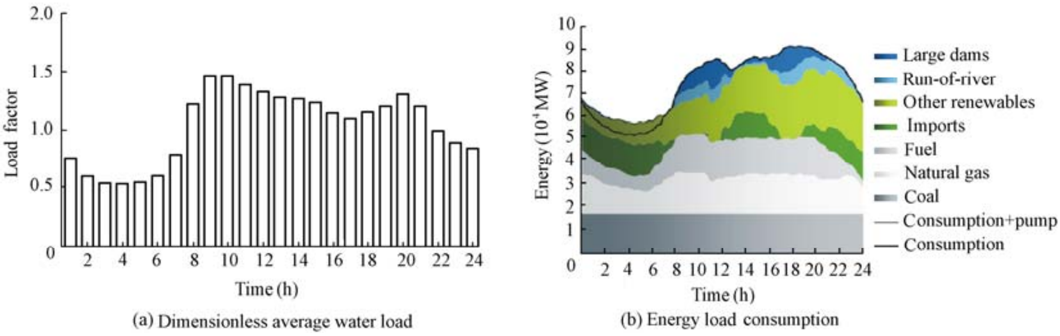

Fig. 17 Typical water and energy load consumption for December 18, 2007

Since the energy used in Portugal comes from different sources, the improvement of components of renewables can be increased by the application of new energy converters to WSSs, whose guaranteed discharge all day can be used for energy production.

In a free market competition, hydropower is the most competitive among long-term renewable sources since it can be integrated with an existing WSS, thus guaranteeing not only a water supply for the population but also the energy used by hydro-turbines for energy production. The economically and ecologically efficient utilization of small or micro hydropower still constitutes an unsolved problem since the conventional turbines (Kaplan or cross-flow) are not yet cost-effective solutions. Also, the medium-sized heads in water supply or irrigation systems that usually have to be dissipated in pressure-reducing valves (PRV) are possible fields for future intervention. In order to explore this hydropower sector, innovative, clean, and economical solutions shall be developed based on the following concepts:

(1) Pump-storage systems with complementary forms of renewable energy (wind or solar energy);

(2) Energy efficiency in WSSs;

(3) Hybrid solutions (hydro/wind/solar energy);

(4) Energy converters for very low heads (in rivers and WSS).

In PRV pipe sections and at the entrance of water treatment plants or reservoirs, there are favorable conditions for utilizing the excess available energy in WSSs and installing energy converters. This energy can be used locally to supply pumping systems or water treatment plants, or, as an alternative, can be sold to the national electric grid depending on the benefits of the tariff.

This analysis required information regarding the available discharge and head over a period of several years, as well as an assessment of the tendency of eventual seasonal interferences and an estimation of the maximum profitability from the available hydropower potential (Table 4). The system presented is characterized by a small power output and has a regular operation, with the inlet discharge properly controlled by an automatic control valve (Fig. 18). There is a bypass line to the normal circuit inside the valve chamber, which is adapted in order to install the micro-turbine with as few modifications as possible.

Table 4 Estimation of energy production and sale value

Year	Q (L/s)	H (m)	Average power (kW)	Annual sale value (€)	Sum value (€)	Year	Q (L/s)	H (m)	Average power (kW)	Annual sale value (€)	Sum value (€)
2007	73	16.3	4.8	2 615	2 615	2014	121	15.6	7.9	4 319	29 409
2008	81	16.2	5.5	3 030	5 645	2015	125	15.5	8.0	4 365	33 774
2009	89	16.1	6.2	3 400	9 045	2016[3]	128	15.4	8.0	4 387	38 161
2010[1]	97	16.0	6.8	3 709	12 754	2017	131	15.2	8.0	4 400	42 560
2011	105	15.9	7.2	3 947	16 701	2018	133	15.1	8.1	4 407	46 967
2012	112	15.8	7.5	4 131	20 832	2019	135	15.0	8.1	4 408	51 375
2013[2]	117	15.7	7.8	4 258	25 090	2020	137	14.8	8.1	4 402	55 777

Note: 1) The investment in turbines can be paid back; 2) The investment in turbines, equipment, and civil works can be paid back; 3) All the investment in the power station can be paid back.

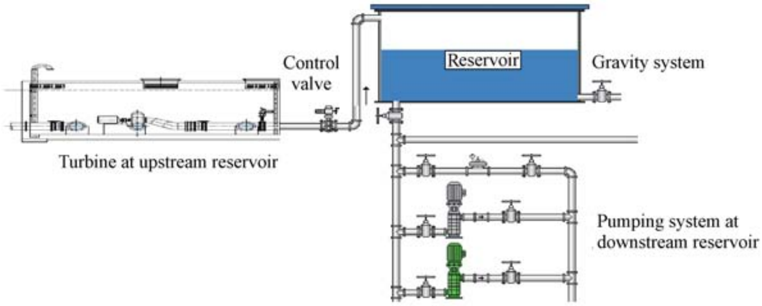

Fig. 18 Typical application of a micro-turbine

The market is not yet ready for this type of small project, characterized by low-power generation (between 0.1 kW to 200 kW). In order to overcome this constraint, a PAT was considered one of the possible energy converters. Table 4 shows that the implementation of a micro hydro project with low-power output is feasible, presenting payback periods between 4 years and 10 years depending on the degree of sophistication of the automatic control equipment.

6 Conclusions

Analysis of the optimization of new possible energy converters adequate for low-power outputs has demonstrated possible success in non-conventional solutions. The optimized energy converters can deliver hydraulic power from about 28 W to 40 kW at small heads and discharges of 0.6-20 m and 6-200 L/s, respectively (Table 3), according to quality performance curves.

The most interesting conclusions of this study are with respect to the internal optimization of these new energy converters and the elimination of as much of the expensive additional control systems as possible. A computational analysis and theoretical methodologies have been developed, which add to further understanding of the internal hydraulic flow at the inlet when it crosses the impeller and at the outlet, subjected to different geometric modifications under different flow conditions. This comprised the study of the flow behavior in response to the shaft power, discharge, hydraulic, and shear stress effects under different values of gross head and turbine speeds. This study is still ongoing, but it can already provide a possible orientation of likely settings for new low-power turbines to address the shortage of effective solutions to small power values on the market. More detailed analysis will be necessary for determining the best choice for local conditions and system characteristics.

References

Alatorre-Frenk, C. 1994. *Cost Minimization in Micro-Hydro Systems Using Pumps-as-Turbines*. Ph. D. Dissertation. Coventry: University of Warwick.

Alexander, K. V., Giddens, E. P., and Fuller, A. M. 2009. Axial-flow turbines for low head microhydro systems. *Renewable Energy*, 34(1), 35-47. [doi:10.1016/j.renene.2008.03.017]

Asian Phoenix Resources Ltd. (APRL). 2001. *Affordable Technology for Developing Countries*. http://www.powerpal.com [Retrieved in February 2009].

Demetriades, G. M. 1997. *Design of Low-Cost Propeller Turbines for Standalone Micro-Hydroelectric Generation Units*. Ph. D. Dissertation. Nottingham: University of Nottingham.

Parker, D. B. 1994. Positive displacement pumps: Performance and application. *Proceedings of the 11th International Pump Users Symposium*. Houston: Texas A&M University.

Ramos, H., and Borga, A. 1999. Pumps as turbines: Unconventional solution to energy production. *Urban Water*, 1(3), 261-263. [doi:10.1016/S1462-0758(00)00016-9]

Ramos, H., and Borga, A. 2000. Pumps yielding power. *Dam Engineering*, 10(4), 197-217.

Rawal, S., and Kshirsagar, J. T. 2007. Numerical simulation on a pump operating in a turbine mode. *Proceedings of the 23rd International Pump Users Symposium*, 21-27. Houston: Texas A&M University.

Rodger, J. 2007. *Pump School*. Cedar Falls: Viking Pump, Inc., Unit of IDEX Corporation.

Sharma, K. R. 1985. *Small Hydroelectric Projects: Use of Centrifugal Pumps as Turbines*. Bangalore: Kirloskar Electric Co.

Simpson, R. G., and Williams, A. A. 2006. Application of computational fluid dynamics to the design of Pico propeller turbines. *Proceedings of the International Conference on Renewable Energy for Developing Countries*. Washington, D.C.: University of the District of Columbia.

Singh, P. 2001: *Establishment of a Test-Rig for Turbine for Micro Hydro and Detailed Testing of a Pump as Turbine*, 24-26. New Delhi: Centre for Energy Studies, Indian Institute of Technology.

Singh, P., Nestmann, F., Caglar, S., and Kshirsagar, J. T. 2004. Hydraulic performance optimization in pumps as turbines. *Pump Users International Forum*. Karlsruhe: VDMA.

Singh, P. 2005. *Optimization of the Internal Hydraulic and of System Design in Pumps as Turbines with Field Implementation and Evaluation*. Ph. D. Dissertation. Karlsruhe: University of Karlsruhe.

Singh, P. and Nestmann, F. 2009, Experimental optimization of a free vortex propeller runner for micro hydro application. *Experimental Thermal and Fluid Science*, 33(6), 991-1002. [doi:10.1016/j.expthermflusci. 2009.04.007].

Upadhyay, D. 2004. *Low Head Turbine Development Using Computational Fluid Dynamics*. Ph. D. Dissertation. Nottingham: University of Nottingham.

Valadas, M., and Ramos, H. 2003. Use of pumps as turbines in irrigation systems to profit the available energy in irrigation system. *Water Resources Journal*, 24(3), 63-76. (in Portuguese)

Williams, A. A. 1992. *Pumps as Turbines Used With Induction Generators for Stand-Alone Micro-Hydroelectric Power Plants*. Ph. D. Dissertation. Nottingham: Nottingham Trent University.