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Experimental characterization of a five blade tubular propeller turbine for pipe inline installation

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ABSTRACT

The interest in micro-hydropower in existing infrastructure is increasing since this is a technology with low environmental impacts and potential for energy recovery in different types of installation. The technologies available for these schemes are still restricted and it is a current subject for research. In this work an experimental characterization of an inline tubular propeller suitable for pressurized systems, such as water supply and distribution networks, is presented. In the framework of the European Project HYLOW, started in 2008, a first prototype has been developed using CFD analysis and tested. Nevertheless, optimization and validation were still necessary. An improved model has been now adequately tested in the laboratory and proves to be interesting in terms of potential application. The experimental investigation evidenced that the new turbine has efficiencies of around 60% for low-headed operations, below 50 m.

1. Introduction

The investment in small hydropower is growing all over the world as it is a clean, sustainable and emissions-free source of renewable energy. Small hydropower can be classified in mini, micro or pico, depending on the output power and on the type of the adopted scheme [25,26]. There are not yet globally accepted boundaries to define these classes, it depends on the country, but micro-hydro typically refers to schemes below 100 kW [28] while pico-hydro usually produces less than 5 kW [1].

A micro-hydropower scheme can generate energy from small rivers, water supply systems, irrigation channels, wastewater treatment plants and pluvial drainage systems. These micro schemes can be used to produce energy to supply the national grid or for local consumption. Consuming on site has the advantage of reducing transmission losses, since energy transportation is an inefficient energy conversion process [40]. Also, in situations such as remote communities, where it is not economical or even possible to connect to the national grid, stand-alone small hydro-systems can be used to respond to the energy needs [17,18].

The turbine technology for micro-hydropower is still much unexplored. Conventional turbines are often not cost-effective for micro-hydro, mostly due to their large diameters and expensive civil engineering works [15,41]. Many investigators have attempted to use different turbines in the micro production range. However their experience was not much encouraging as it resulted in complicated arrangements and high costs of installation [17]. Consequently, special converters are needed for the exploitation of this source of renewable energy [15].

There are several hydropower technologies currently being employed in low-headed schemes. The most frequently used are the Zuppinger water wheel, the Archimedes screw working in reverse, the crossflow turbine and pumps operating as turbines (PAT).

The Zuppinger or undershot wheel was developed in the 1850's and can be used for very small head differences (0.5–2.5 m) and large flow volumes (0.5–0.95 $m^3/s/m$). This wheel employs only the potential energy of the flow as the principal driving force and the water enters over a weir, so that the cells can be filled rapidly [22]. Its peak efficiency is 70–74%, and power ratings range from 3 to 100 kW. With diameters from 4 to 7.5 m and rotation speed from

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3 to 6 rpm, the wheels have a slow speed, which means that expensive gearing is obligatory [16].

The Archimedes screw is a technology for pumping that exists since antiquity. Its application in reverse operation has led to more research on its efficiency and optimal configurations. It consists of a helical screw that can be applied on rivers with low heads [19,23]. Schleicher et al.[34] proposed a geometry of the blades optimized by CFD analysis in which a peak efficiency of 72% was reached.

A PAT is a hydraulic pump running in reverse mode so that, in conjunction with an induction generator, it recovers energy. The mass production of pumps and its smaller complexity makes them a less costly solution [17]. Nevertheless, the main disadvantage of using a PAT is the difficulty of finding the characteristics needed to select the correct pump for a particular site. Fixed flow rate PATs are only suitable for sites where there is a sufficient supply of water throughout the year [42] and there is still no standard design criteria available for highly variable flow-rates and pressure heads [5]. The efficiency of a PAT is very sensitive to changes of flow, which means that an inappropriate pump selection will result in an undesired output, and ultimately in the failure of the project [28]. In situations where multiple discharge values are plausible, it is also possible to consider the use of two or more PATs [6,10].

Other than these well-known technologies, research has recently been carried for the development of new turbines for low heads. Some examples are herein presented.

The hydroelectricity group in University of Applied Sciences and Arts Western Switzerland in Sion (HES-SO VS) and the Laboratory of Hydraulic Machines (LMH) at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, have designed and developed an axial counter-rotating turbine to be installed inline pipes. Numerical simulations were performed with ANSYS CFX and three prototypes were built for laboratory testing. The first turbine prototype with a 50 mm radius was designed to recover 10 mWc on each runner for 8.7 l/s at the best efficiency point [24] and tested in an elbow configuration at EPFL-LMH. A second prototype in a bulb configuration has been developed and tested by the Hydroelectricity group of the HES-SO VS. The bulb configuration is particularly interesting as it allows encapsulating the two generators, one for each runner, internally [21]; [4]. Now a multi-stage “straflo” design is under development to provide a family range of turbine from 5 to 25 kW.

The free vortex propeller was designed by Singh and Nestmann [38] to recover gross heads from 1.5 to 2 mWc for open channel flows. The blades of the propeller were optimized using the free vortex theory considering flows from 60 to 75 l/s. An experimental test-rig was assembled and tests were satisfactory, resulting in 810 W of maximum power with 73.9% of efficiency.

A flexible foil vertical axis turbine has been studied by Zeiner-Gundersen [43] for river, ocean, and tidal applications. Its flexible behavior was inspired on the dynamic characteristics of aquatic animals. A model with 9 m of diameter was tested, with five wings connected to a 7 m tall central main shaft holding the blades. Its best efficiency was achieved for a velocity of 0.79 m/s and up to 17 kW were generated.

The EU-Project HYLOW (HYdropower converters with very LOW head differences, 2008 to 2012), aimed studying new hydropower converters for very low head differences. Within the scope of this project, a few designs were proposed, among them:

- The Rotary Hydraulic Pressure Machine (RHPM), developed in the University of Southampton, in the UK. This machine has a wheel with a diameter between 1.5 m and 7.5 m which rotates about a horizontal. It was envisaged that the RHPM could be employed with fall heights under 5 m in any conventional diversion or run-of-river installation and would also be particularly suited for installation into bays of existing weir structures [35].
- The Hydrostatic Pressure Machine (HPM), also developed in the University of Southampton, for river applications with head differences between 1 and 3 mWc. Prototypes of this converter were investigated, including a full-scale one installed in a river [44].
- The Free Stream Energy Converter (FSEC), inspired by boat mills, was tested at various scales at the University of Rostock, in Germany. Its application is also envisaged for small rivers [3].
- And a Five Blade Tubular Propeller (5BTP), developed in Instituto Superior Técnico (IST), in Portugal [15], which is the object of the present work.

The presented state of the art reveals that research is being carried to design new technologies for micro-hydro since the traditional large-scale turbines are not easily applicable for such low heads and flows. The presented ongoing research can be divided in two main fields of application, for small rivers and for pressurized systems. In the case of pressurized systems, crossflow turbines, although considered expensive, can work on a wide range of net heads, from 1.75 to 200 mWc. PAT are less costly but they are sensitive to flow variations. The development of a tubular turbine that can be installed inline in pressurized pipe is thus considered interesting.

The installation of turbines inline a pipe is particularly attractive for applications in water supply systems. It has been verified that the incorporation of turbines in these systems can contribute to improve the energy efficiency of the system and to solve problems of leakage [7,10,20]. The optimization of this type of micro-hydropower generation is currently a topic of research [7,33].

The goal present work focuses on the presentation of the results of laboratorial experiments from the testing of the 5BTP. The development of this turbine started during the HYLOW Project with numerical simulations and a few primary experimental tests, but laboratorial optimization and validation with wide ranges of discharge and rotational speed were still needed. In Section 2 the background development of the turbine is summarized. The experimental methodology is presented in Section 3, followed by the results in Section 4. In Section 5 the results are discussed and the main conclusions are presented in Section 6.

2. Background and optimization of the 5BTP

The HYLOW Project (2008–2012) was a research project funded by the European Commission's 7th Framework Program with the aim of developing novel hydropower converters for very low heads. IST, one of the partners, was involved with the study of small converters for pressurized flows. Initially, turbines and positive displacement concepts were investigated but it was found that positive displacement converters are only suitable for vary small discharges and high heads, leading to unfavorable pressure surges. Therefore, the research on turbines was deepened further for turbines, based on CFD modeling and laboratorial tests.

Propeller turbines are axial turbines that are usually adequate for operation under low head and high flow rates [6,9]. They have been mainly used in small and mini hydro schemes, but their application for micro hydro is still at the beginning. Nevertheless, scaling-down from a large turbine cannot be directly applied on this case due to associated scale effects, as it has been verified by Ramos et al. [29]; but also because the economic and manufacturing constraints are not the same [38]. To overcome this limitation, numerical simulations were done in the FLUENT model, a Navier-Stokes solver, considering different turbine configurations [28]. A $k-\varepsilon$ turbulence model was used and the meshes were