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Review

Stream water wheels as renewable energy supply in flowing water: Theoretical considerations, performance assessment and design recommendations

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ABSTRACT

Water wheels were the earliest hydraulic machines used in antiquity to convert water energy into mechanical one. Due to their simple installation, low maintenance costs, and thanks to the possibility to use local manpower and material for their construction, nowadays water wheels are again used as energy supply, especially in remote localities and emerging countries. In particular, stream water wheels are installed in flowing water where there are not head differences. The performance depends on the blockage ratio, so that they can be subdivided into three main categories: stream wheels in shallow subcritical flow, shallow supercritical flow and deep flow.

In this paper, experimental, theoretical and numerical data on stream water wheels were systematically collected from literature and analyzed. Guidelines for their design were discussed focusing especially on wheel dimensions, supporting structures, blades and speed. More light on their hydraulic behavior was shed, adopting the previous classification for a better explanation and understanding. Results showed that in shallow water an head difference can be generated by the wheel, increasing the power output. In deep flow, accurate hydrodynamic floating/supporting structures allow the hydrostatic force of water to be exploited in addition to the kinetic energy of the flow. As a consequence, power output can improve from 0.5 to more than 10 kW per meter width, so that stream wheels can represent an attractive energy supply in zero head sites.

Introduction

Nowadays, the increasing demand of energy and electricity, and the growth of population, pose two major challenges. The first one is the need of reducing greenhouse gas emission and environmental pollution, while satisfying the global energy demand. This challenge can be afforded by using large power plants based on renewable sources, like hydropower plants (Banja, Monforti, & Scarlat, n.d.; European Commission, 2009a, 2009b). The second challenge is to give equal energy access to all countries and people, since current energy access is neither universal nor guaranteed. The World Energy Outlook estimates that 1.2 billion people do not have access to electricity (Blodgett, Dauenhauer, Louie, & Kickham, 2017). Micro-grids (i.e. power output less than 100 kW) based on renewable energy are a promising option for this challenge, due to their low initial investment levels, scalability and suitability for rural areas (Blodgett et al., 2017).

Hydropower represents an interesting option to satisfy both the challenges. Hydropower plants are currently the most contributory renewable energy source worldwide (Laghari, Mokhlis, Bakar, & Mohammad, 2013), and they continue to be installed, especially in emerging countries (de Faria & Jaramillo, 2017). However, due to the need of large dams, large hydro plants generate some adverse effects on ecosystems: flooding of large areas upstream, interruption of the river longitudinal connectivity, changing in the hydrological regime and sediment transport processes of rivers, and, sometimes, social impacts (Kallis & David, 2001). Instead, micro hydro grids are more environmental friendly than big hydro plants. Sites suitable for micro hydro plants are present in almost all countries (Blodgett et al., 2017; Laghari et al., 2013), so that micro hydro plants could be a promising option both as energy supply and as easy access to energy.

Micro hydro plants are becoming very popular and attractive especially in rural and decentralized areas, and in developing countries, where the large distances usually require decentralized electricity production and off-grid power plants. Micro hydro plants can provide a simple energy access to small and local communities, or to remote industrial sites. Micro hydro schemes can use existing civil/hydraulic structures, for instance old water mills, so that total installation costs

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are minimized (European Small Hydropower Association (ESHA), 2014). Micro hydro is also of high importance in industrialized countries for meeting the non-fossil fuel targets, for satisfying the rising electricity demand and for new market opportunities (Paish, 2002; Quaranta & Revelli, 2017).

Turbines for micro hydro plants

The turbine is the component of the hydro plant that converts the power of the flow into mechanical one. Basically, turbines can be classified into action turbines, like Pelton turbines, and reaction turbines, like Kaplan and Francis turbines. Pelton turbines are used with heads up to 2000 m, Francis turbines up to 700 m, and Kaplan turbines up to 40 m, and a typical range of heads is tens/hundreds meters. Where heads of few meters are present (e.g. <3 m), Francis and Kaplan turbines can be scaled and installed, but they are not cost-effective: they are of not easy installation, investment costs are high and payback times of more than 20 years are expected. Environmental impacts are significant, because these turbines require pressurized pipes, draft tubes and screens to avoid passage of sediments and fish through the turbine (Bozhinova, Kisliakov, Müller, Hecht, & Schneider, 2013; Elbatran, Yaakon, Ahmed, & Shabara, 2015; Quaranta, 2017; Williamson, Stark, & Booker, 2014). Pelton turbines are not convenient due to the low flow rate that can be swirled.

As a consequence, in the last decades, new hydropower converters for low head sites have been introduced on the market, like Archimedes screws (Lubitz, Lyons, & Simmons, 2014; Lyons & Lubitz, n.d.; Waters & Aggidis, 2015), gravity water wheels and stream water wheels (Müller, Denchfield, Marth, & Shelmerdine, 2007; Müller & Kauppert, 2004; Quaranta, 2017) and hydrokinetic turbines (Vermaak, Kusakana, & Koko, 2014). These machines are more environmental friendly and cost-effective than typical action and reaction turbines (Bozhinova et al., 2013). Their rotational speed is slower, and they do not require pressurized pipes, so that risks imposed on fish and problems with trapped sediments are minimized (Bozhinova et al., 2013). Therefore, maintenance costs are reduced, and payback times are significantly lower than those of micro plants equipped for example with Kaplan turbines (Müller & Kauppert, 2004).

Archimedes screws (or hydrodynamic screws if the external supporting shroud does not rotate) and gravity water wheels are used in sites where there exists a drop in the channel bed, that hence creates an head difference. The pressure exerted on the blades is generated by the water weight, thus it is an hydrostatic pressure that only depends on the water depth over the blades. Therefore, such hydropower converters are called gravity machines, or hydrostatic pressure converters. Archimedes screws and gravity wheels are generally used from 0.5 m to 6–8 m head, and they are partially immersed in water. Archimedes screws rotate around an axis inclined of 22°–35° on the horizontal, while the rotational axis of gravity water wheels is horizontal. With regard to gravity water wheels, undershot wheels are used for head differences between 0.5 and 1.5 m (Quaranta & Müller, 2018-b; v. Harten, Paudel, & Saenger, 2013), breastshot wheels are usually employed for head differences between 1.5 and 4 m (Müller & Wolter, 2004; Quaranta & Revelli, 2015b), and overshot wheels are used for head differences between 2.5 and 6 m (Müller & Kauppert, 2004; Quaranta & Revelli, 2015a). Fig. 1a–c depict an example of Archimedes screw, undershot and overshot water wheel.

Hydrokinetic turbines were originally conceived like wind turbines. Nowadays they are also installed in flowing water, with zero head conditions and without drops in the channel bed, so that only the flow kinetic energy is employed for power production. Hydrokinetic turbines are completely immersed in flowing water, and they are typically built with vertical axis. Two types of hydrokinetic turbines can be identified: the drag type and the lift type. In the drag type, like the Savonius hydrokinetic turbine, the drag force exerted at the blades drives the turbine. In the lift type, like the Darrieus turbine, the turbine rotation is provided by the lift force at the blades (Anyi & Kirke, 2011; Vermaak et al., 2014). Fig. 1d depicts a Darrieus turbine. In Vermaak et al. (2014), hydrokinetic turbines have been deeply discussed.

Stream water wheels are used in the same hydraulic conditions of hydrokinetic turbines: flowing water with no head difference in the undisturbed flow regime (or very small so that the potential energy is less than the kinetic one). Differently from hydrokinetic devices, the rotational axis of stream wheels is horizontal, like gravity water wheels (Fig. 2), and it is installed over the free surface of water, so that only the lowest part of the wheel interacts with the water flow.

Stream water wheels can be used for different purposes: power supply for local activities and mills (handmade works or crop grinding) (Fig. 2a) electricity (Fig. 2b) (Müller, Jenkins, & Batten, 2010), and as device for pumping water in irrigation canals, the so called spiral pumps (Kumara, n.d.) (Fig. 2c). For the generation of electricity, an electrical generator has to be mounted at the shaft. Instead, in spiral pumps, a spiral tube is wrapped around the central shaft of the wheel. Water of the river is collected by the tube external edge (located at the wheel circumference). Water flows along the pipe, from the pipe edge to the wheel shaft, where a pipe connected with the river side carries water to the end-user. Common spiral pumps are able to pump to a maximum height of 20 meters and a maximum flow rate of 43.6 m^3/day (Aqysta, n.d.; Kumara, n.d.).

Stream wheels are especially worthwhile in sites where local manufacture and materials can be employed for their installation, like in rural areas and emerging countries. They are of simple construction (little civil engineering work is required), with low installation costs, few maintenance problems and high cultural and aesthetic value (Müller et al., 2007, 2010). The full implementation of such technology can lead to the establishment of many small river hydroelectric power stations, that in turn will create sustainable development, manufactures and jobs (Akinyemi & Liu, 2015).

Stream wheels: types and scope of the work

Apparently, in flowing water only the kinetic energy of the flow could be exploited by a stream water wheel, but, actually, performance and hydraulic behavior of stream wheels depend on Froude number (subcritical or supercritical flow) and blockage ratio (Bahaj, Molland, Chaplin, & Batten, 2007; Müller et al., 2007). The blockage ratio is defined as $B.R. = A/A_c$, where A is the immersed blade/wheel area (measured orthogonally to the flow direction) and A_c is the wet channel cross section. At low B.R. the presence of the wheel substantially does not modify the flow field inside the channel, except very close to the wheel, due to the blade entry and exit process, and fluid-structure interaction. This is the typical case of stream wheels installed in deep flow and large rivers; such stream wheels are also called floating wheels and the power output depends on B.R. As B.R. increases a higher portion of flow is forced to pass through the wheel, increasing the power output. For example, at $B.R. = 0.2$ the increase in power output due to the blockage effect is 30% with respect to the undisturbed configuration, while it is less than 10% at $B.R. \leq 0.05$ (Müller et al., 2010). As B.R. still increases ($B.R. \rightarrow 1$), power losses in the river flow generated by the presence of the wheel would be so high that, in subcritical flow, a well identifiable backwater propagation arises, and the discharge that can pass downstream only depends on the wheel rotational speed (see Stream wheels in shallow supercritical flow for more details). This is the case of stream water wheels installed in shallow water, where the blade length is similar to the water depth, and an head difference is induced to drive the wheel. If the undisturbed flow regime is supercritical, the upstream flow can be converted into subcritical, or it can remain supercritical, depending on wheel tangential speed.

In light of this, three types of stream wheels can be identified, as suggested in Müller et al. (2007): stream wheels in shallow