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Note

Horizontal axis hydrokinetic turbines: A literature review

Turbinas hidrocinéticas de eje horizontal: Una revisión de la literatura

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Abstract

Hydrokinetic turbines make it possible to generate electrical energy from a renewable source, using water flow energy, which is usually obtained from rivers, seas, and manmade canals, among other sources. This technology contributes to the conservation of the environment, since it does not require the construction of dams because performance is not limited to the water head, which is one of the main characteristics that distinguishes this technology from conventional hydroelectric plants. This article is a review of hydrokinetic turbines with a horizontal axis, taking into account a series of design parameters, computational simulation, manufacturing materials, and some improvements implemented to increase the efficiency of this type of technology, including the use of diffusers and/or nozzles, their arrangement in the water, and others. This work will help to identify some of the areas that have been addressed by other investigators, as well as to promote the use of hydrokinetic turbines for exploiting the energy available from hydric sources in different regions of the world, which, in particular, can be used to provide electrical energy in non-interconnected zones. All of this will contribute to the improvement of the quality of life and the sustainability of the region where the technology can be used.

Keywords: Diffusor, efficiency, renewable energy, computational simulation, hydrokinetic turbines.

Resumen

Las turbinas hidrocinéticas permiten la generación de energía eléctrica a partir de una fuente renovable, utilizando la energía de las corrientes de agua, generalmente de ríos, mares y canales elaborados por el hombre, entre otros. Constituyen una tecnología que contribuye a la conservación del medio ambiente, al no requerir la construcción de represas, dado que su funcionamiento no está limitado a alturas o caídas de agua, siendo una de las principales características diferenciadoras con relación a las centrales hidroeléctricas convencionales. En este artículo se realiza una revisión sobre turbinas hidrocinéticas de eje horizontal, teniendo en cuenta una serie de aspectos de diseño, simulación computacional, materiales empleados en la fabricación y algunas mejoras implementadas para incrementar la eficiencia de este tipo de tecnología, como el uso de difusores y/o toberas, y la disposición en agua, entre otros. Este trabajo ayudará a identificar algunas de las áreas que han sido abordadas por otros investigadores, además de promover el uso de turbinas hidrocinéticas en el aprovechamiento de la energía disponible en los recursos hídricos de distintas zonas del mundo, que pueden ser empleadas en especial para suministrar energía eléctrica en zonas no interconectadas. Todo ello contribuirá a la mejora de la calidad de vida y sostenibilidad de las zonas donde se emplee.

Palabras clave: difusor, eficiencia, energía renovable, simulación computacional, turbinas hidrocinéticas.

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Introduction

The velocity of water in a river is a clean and constant source of energy. To use this without having to build a large infrastructure, such as that needed in large hydroelectric plants, various types of turbines submerged in water currents, called hydrokinetic turbines (THCs), have been developed. These turbines do not depend on high altitudes or waterfalls, which makes them a low-cost technology and reduces implementation time, in addition to having a minimal environmental impact (Chica, Perez, Rubio-Clemente, & Agudelo, 2015; Filho, Souza, Rossi, Barros, & Silva, 2010; Gaden & Bibeau, 2010; Yuce & Muratoglu, 2014). These turbines extract kinetic energy from marine currents, rivers, and artificial canals, among other sources, and convert it into mechanical power without interrupting the natural flow of the water (Badea, Pricop, & Bobonea, 2014). However, these devices present a great disadvantage with respect to the low energy density obtained in comparison with conventional hydroelectric power plants, suggesting that their economic feasibility must be studied in detail (Gaden & Bibeau, 2010; Khan, Bhuyan, Iqbal, & Quaicoe, 2009). THCs can be characterized by the orientation of their rotational axis with respect to the direction of water flow, classifying them as axial flow and cross-flow, or transversal turbines. Axial flow THCs have their rotational axis parallel to the direction of the current, using propeller-type impellers. Several layouts of this type of turbines are shown in

. The tilted shaft turbine (Figure 1a) is most often used in small rivers, while the other arrangements (Figures 1b, Figure 1c, and Figure 1d) are mainly used for ocean energy extraction (Vermaak, Kusakana, & Koko, 2014).

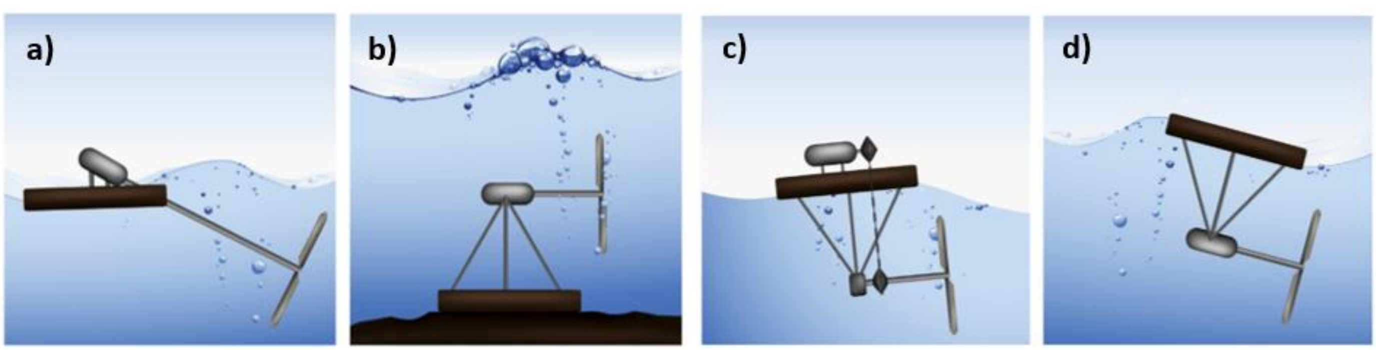

Figure 1. Hydrokinetic axial flow turbines: a) inclined axis, b) rigid mooring, c) non-submerged generator, and d) submerged generator. Source: Vermaak *et al*. (2014).

Meanwhile, cross-flow or transversal hydrokinetic turbines (THCFC or THCFT) have their rotation axis perpendicular to the direction of the water flow and can operate regardless of its direction. These turbines can be classified into two types. One has horizontal axis turbines in a transverse arrangement (Figure 2a), which operate based on the drag force and have a poorer performance than the vertical axis. The other type, consisting of vertical axis turbines (Figure 2b, Figure 2c, Figure 2d, Figure 2e, and Figure 2f) operates based on the lift force, and is widely used in hydroelectric applications, thanks to the advantages offered by the horizontal shaft turbines in a transversal layout. However, their hydraulic design and behavior are more complex (Zanette, Imbault, & Tourabi, 2010).

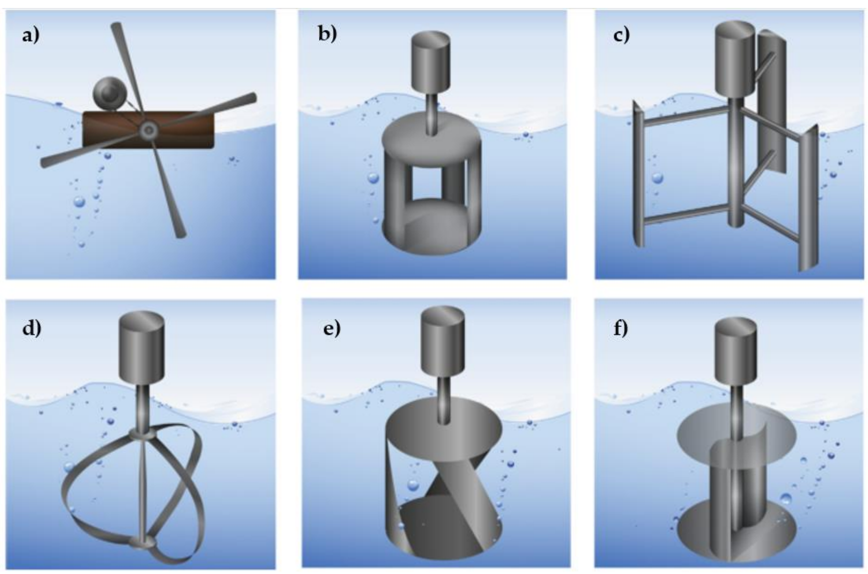

Figure 2. Cross-flow hydrokinetic turbines: a) horizontal axis, b) squirrel cage Darrieus, c) H-Darrieus, d) Darrieus, e) Gorlov, and f) Savonius. Source: Vermaak *et al*. (2014).

The principle of operation of the THCFC or THCFT consists of the transformation of the kinetic energy of the water contained in a natural water source into the turbine's rotational kinetic energy. This occurs due to the water current that flows through the blades, which are attached to a rotor. With some of the geometries of vertical axis turbines, such as those shown in Figure 2b, Figure 2c, Figure 2d, and Figure 2e, the water comes into contact with the blades. This takes place in two stages: first, the fluid enters from the outside towards the interior, and second, water flows from the inside to the outside of the turbine, thereby transferring its energy (Okot, 2013). This is different than horizontal axis hydrokinetic turbines, which transfer the kinetic energy of the fluid with only one stage, and generate higher speeds of rotation than cross-flow.

The energy contained in a stream of water is directly proportional to the density of the fluid, the area of the cross section, and the velocity of the fluid. Therefore, when comparing THCs with speeds from 1.75 m/s to 2.25 m/s, and wind turbines with speeds between 11 m/s and 13 m/s, there is a great difference in the power generation potential, since the density of water is 832 times greater than that of air under normal temperature and pressure conditions. It is important to mention that the fluid that passes through the turbine does not deliver all its energy. In fact, a power coefficient has been defined which indicates the amount of kinetic energy that can be extracted from the flow and converted into mechanical energy in the axis of the turbine, with a maximum value of 59.3%, which is known as the Betz limit (Koko, Kusakana, & Vermaak, 2015; Shahsavarifard, Bibeau, & Birjandi, 2013; Vermaak *et al*., 2014). Subsequently, an extension of this theory is presented, known as the Lanchester-Betz limit, which indicates that not all the available energy can be captured by the turbine, because this would mean a complete obstruction of the fluid (Ruopp, Ruprecht, Riedelbauch, Arnaud, & Hamad, 2014). The total electrical power that is generated is affected not only by this coefficient but also by the efficiencies of the transmission mechanism and the generator, the physical properties of the fluid (density), the area swept by the turbine blades, and the operating conditions (flow) (Gaden & Bibeau, 2010; Guney, 2011). Two other features that makes THCs a more attractive alternative are its modularity and expandability. They can be arranged in arrays of multiple units in order to extract more energy from the water streams (Zanette *et al*., 2010).

Hydrokinetic turbines

Although various technologies use renewable energy to generate electricity, some cannot be used or do not have the necessary conditions to obtain the optimal efficiency needed to maintain a good cost-benefit ratio, thus becoming unsustainable technologies. This is often found in areas with special environmental or geographical characteristics, where high rainfall occurs with long periods of cloudy sky, which along with high humidity and rapid growth of fungi and vegetation generates premature failures in solar energy panels. In addition, densely wooded areas do not have sufficient air currents to supply a wind turbine, and water sources may not be high enough to feed conventional electric microgeneration systems. For this reason, hydrokinetic turbines emerge as an alternative capable of satisfying the energy demand in these areas, if they are provided with a water source (Anyi & Kirke, 2015).

Currently, very few studies have been carried out on THCs, since it is a technology that is in its initial stage and needs to be investigated in greater depth (Yuce & Muratoglu, 2014). The lack of correlations characterizing this type of turbomachinery is evident in the literature, which is why most studies on THCs have been developed empirically, especially at the design stage, where the support profiles used in most of these projects have been adapted from results obtained by tests performed on wind turbines.

Design of horizontal axis hydrokinetic turbines

THCs operate under the same principles of wind turbines, sharing similar design philosophies (Anyi & Kirke, 2011; Chica *et al*., 2015; Day *et al*., 2015; Güney & Kaygusuz, 2010; Yuce & Muratoglu, 2014). The design of a THCEH starts with determining the dimensions of the rotor, which is done using Equation 1, based on the quantity of the power output P required or expected from the turbine, which is given in terms of the density, ρ, and velocity, *V*, of the fluid, the area of the cross section, *A* swept by the blade (disc model), the power coefficient, C_p, and the efficiency of the transmission train, η (Anyi & Kirke, 2011; Chica *et al*., 2015; Vermaak *et al*., 2014), where the term $C_p\eta$ should be equal to 21% (Anyi & Kirke, 2011):

$$P = \frac{1}{2}\rho A V^3 C_P \eta \quad (1)$$

An important parameter in the design of the THCEH is strength, which is the ratio between the pitch and the rope of the blades, and it should be around 30%, in order to have a good starting torque and a high relative speed (Anyi & Kirke, 2010). Another important factor is the angle of torsion of the blade from the tip to the base, since a study by Lanzafame and Messina (2009) on designs of blades for wind turbines showed that a twisted blade performs better than one that is totally straight. Other factors of interest exist, such as the selection of the hydrodynamic profile to be used. Several aspects must be taken into account when designing a THC, for example, the type of turbine to be used. The performance coefficients for the different existing turbines must be taken into account, which are commonly given as a function of the tip speed ratio (TSR), defined as "the relationship of the tangential velocity at the tip of the blade to the reference velocity of free flow" (Chica *et al*., 2015). The TSR is represented according to Equation (2), where *R* is the radius swept by the blade of the turbine, ω the speed of the blade's rotation, and *V* is the velocity of the fluid:

$$\lambda = \frac{R\omega}{V} \quad (2)$$

Figure 3 shows the TSR vs power coefficient diagram, where the cross flow turbines work at low speeds and have low power coefficients compared to the axial turbines (Guney, 2011). This fact must also be considered when selecting the type of turbine. Another important aspect to keep in mind is the variation in the current velocity profile, for the purpose of determining the point where the system should be installed in order to obtain better efficiency. Figure 4 schematically illustrates how velocity varies with depth, observing that in the background the velocity is low due to friction with the bottom of the channel, and it increases to a maximum value, then decreases as it reaches the surface due to friction with the air. The velocity also varies laterally along the width of the channel. This was analyzed by Gunawan *et al*. (2012), who determined that the maximum velocity is near the center of the current. Neary, Gunawan and Sale (2013) were able to demonstrate that turbulence can increase the hydraulic efficiency of the turbine by approximately 12%, so to take advantage of this additional energy, the effect of this turbulence on the structural design of the system should be considered.

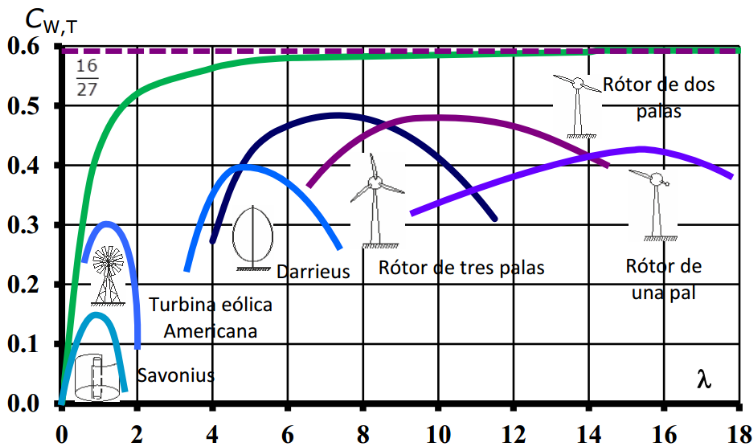

Figure 3. TSR *vs*. C_p diagram with different turbines. Source: adapted from Guney (2011).

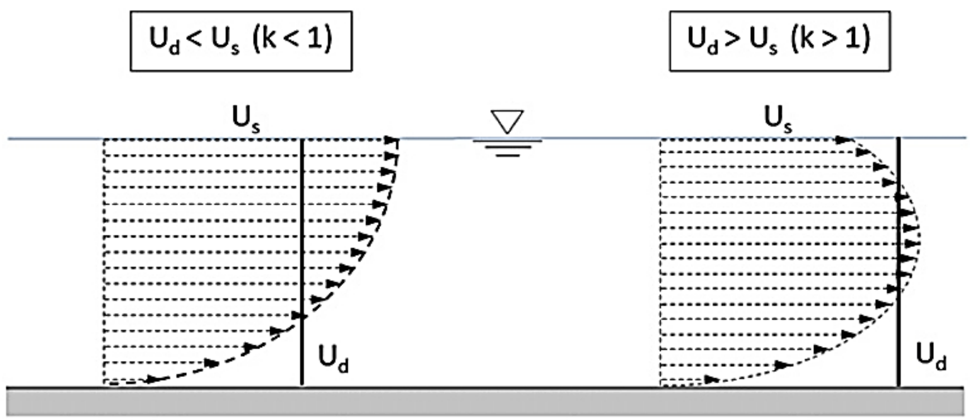

Figure 4. Schematic representation of the relationship between depth and change in current velocity. Source: Gunawan *et al*. (2012).

Computational simulation of horizontal axis hydrokinetic turbines

Schleicher, Riglin, Kraybill and Gardner (2013) performed a simulation of a two-blade THCEH with a sweep angle of 144°, for water flow velocities between 0.5 and 3 m/s. They used computational fluid dynamics (CFD) in ANSYS® CFX with the Navier Stokes turbulence model k-ε (RANS) in order to calculate the distribution of pressures and velocities as they passed through the turbine. They also used the results obtained from a structural analysis. One of their most notable findings is that cavitation was not present in the normal operating conditions of the turbine analyzed.

Badea, Bobonea, and Procop (2014) used an ANSYS® CFD Fluent simulation with the Shear-Stress Transport (SST) k-ω turbulence model to analyze a THCEH with three blades and a water current velocity of 1.5 m/s. As a result, they obtained the longitudinal velocity field, the vortex of the turbine, the turbulent kinetic energy in a cylindrical section, and the pressure distributions on the vane.

Muñoz, Chiang, and De la Jara (2014) analyzed a THCEH with two vanes, using a variation of the attack angle between 0° and 180°, with a proprietary program called "Turbem," which is an open source software. This is used to obtain the geometry of the turbine, the yield curves, and the corresponding structural analysis. They also validated and compared two models of the blade, one consisting of wood and another made of wood with fiberglass and epoxy resin coating, with a water flow velocity of 2 m/s and by means of the Finite Element Method (FEM) using the Inventor® V2013 program. These authors found that the second model performed better.

Chica, Pérez, Rubio-Clemente, and Agudelo (2015) used an ANSYS® CFX simulation with the turbulence model k-ε, in a steady state, to analyze a THCEH with three blades, with an angle of attack of 5°, and a water flow velocity of 1.5 m/s. With the results obtained from the distribution of pressures and velocities on the blade, they performed a structural analysis with dry pine, ABS (acrylonitrile butadiene styrene), and aluminum 6061-T6 as materials, to which they first applied a coat of fiberglass (type E) and then fiberglass with epoxy resin. They concluded that for the interests of remote populations, wood can be used as a base for the manufacture of the blade with one of the two coatings analyzed, while finding that the fiberglass with epoxy resin performed better.

Schleicher, Riglin and Oztekin (2015) performed a characterization by means of CFD simulations, with the turbulence model k-ω Shear-Stress Transport (SST), in steady state, for a two-bladed hydrokinetic turbine, with a water current velocity of 2.25 m/s. This was conducted in order to predict quasi-stationary structures for a wide range of tip speed coefficients. As a result the normalized speed, the standardized static pressure, and the normalized vorticity through the turbine were obtained.

Construction of horizontal axis hydrokinetic turbines

The manufacture of a THCEH is not a simple task, since factors such as profitability, investment, operating costs, and alternative sources must be considered. In order to directly improve its profitability, the costs of design, materials, manufacturing, and maintenance must be reduced (Muñoz *et al*., 2014). To determine the feasibility and profitability of a material for the manufacture of this type of turbine, it is necessary to implement both a structural analysis, which can be carried out using computational simulation, and a cost analysis, in which the prices of materials should be taken into account, which are normally directly affected by local availability (Muñoz *et al*., 2014). This provides autonomy to the inhabitants to manage their own systems, taking into account that they are also responsible for carrying out the needed maintenance (Chica *et al*., 2015). Therefore, depending on the equipment, material, and economic resources available, components such as vanes, diffusers, and hubs (axes), among others, can be manufactured with great precision using conventional CNC equipment (Javaherchi, Stelzenmuller, & Aliseda, 2013; Muñoz *et al*., 2014; Shahsavarifard, Bibeau, & Chatoorgoon, 2015). Or with 5-axis CNC machines (Kolekar & Banerjee, 2015), with less precision, using simpler and more inexpensive processes such as plasma cutters (Davila-Vilchis & Mishra, 2014) or carpentry techniques for one of the blades, which serves as a reference in copying machines as routers and rotating saws in order to obtain each of the blades of the turbine (Anyi & Kirke, 2011). It is worth noting that this type of technology can be manufactured empirically, either using high specification equipment or through expertise, imagination, and tools available from the manufacturer, depending on the technical requirements of the final application.

Studies exist in which several authors have suggested various materials for the construction of hydrokinetic turbine blades, among which Anyi and Kirke (2011) suggest the use of wood, which in its demonstration phase can be pine, for the manufacture of a blade with soft material, and thus would be easy to produce. Wood known as "Belian," highly abundant in Sarawak, Malaysia, can be used for its strength, resistance to wood insects, and great durability even when it is submerged in water. In addition to this, Muñoz *et al*. (2014) proposed adding fiberglass and epoxy resin layers to wooden blades to increase their resistance, arguing that the resin will also serve to seal the wood, protecting it against deterioration caused by direct contact with water. This goes hand in hand with the proposal by Anyi and Kirke (2010), and Li, Hu, Chandrashekhara, Du and Mishra (2014) to use fiberglass composite material and epoxy resin for a good price-to-performance ratio. That is also resistant to corrosion, and is strong and robust, providing excellent resistance to static failure, as compared to carbon fiber, which despite having better characteristics than the previous ones and being lighter, can cost between

10 and 20 times more than fiberglass. Aluminum vanes (Anyi & Kirke, 2015; Javaherchi *et al*., 2013) and aluminum alloys (Kolekar & Banerjee, 2015; Schleicher *et al*., 2013) have also been used, as well as stainless steel (Davila-Vilchis & Mishra, 2014) because of its resistance to corrosion.

Machines used to increase the efficiency of hydrocintic turbines

Liu and Packey (2014) proposed using THCs directly at the output of already established turbines at conventional hydroelectric power stations, or at sites neighboring these power plants, which is called the Combined Electric Power Cycle System (CCHS). They analyzed the possible changes, advantages, and potential benefits that this would entail, and reported that the CCHS concepts have been used and demonstrated in two projects carried out in the USA. The authors concluded that despite being an attractive technology, its viability requires a cost-benefit analysis.

Perhaps the biggest obstacle faced by THCs, in terms of their implementation in rivers, are the suspended solids from human activities. This problem has been largely avoided by installing these devices in areas where there is not too much dirt, which significantly limits its location, a fundamental factor in distributed generation (Anyi & Kirke, 2015). In order to solve this problem, Anyi and Kirke (2015) developed a THCEH capable of swinging its blades back and forth in its plane of rotation to enable the slipping of residues, and which has an internal ring that prevents grass or other elements from winding up around the axis, obtaining as a result a turbine that is practically free of weeds. This turbine operates normally when it is in a relatively clean environment (Figure 6a), can adapt to the presence and interference of residues, allows the radial displacement of each of its blades (Figure 6b), which are capable of deformation or inclination downstream of the turbine due to axial loads (Figure 6c). Thus, it acts as a cleaning and protection mechanism to allow the passage of debris, enabling the vanes to return to their initial position.

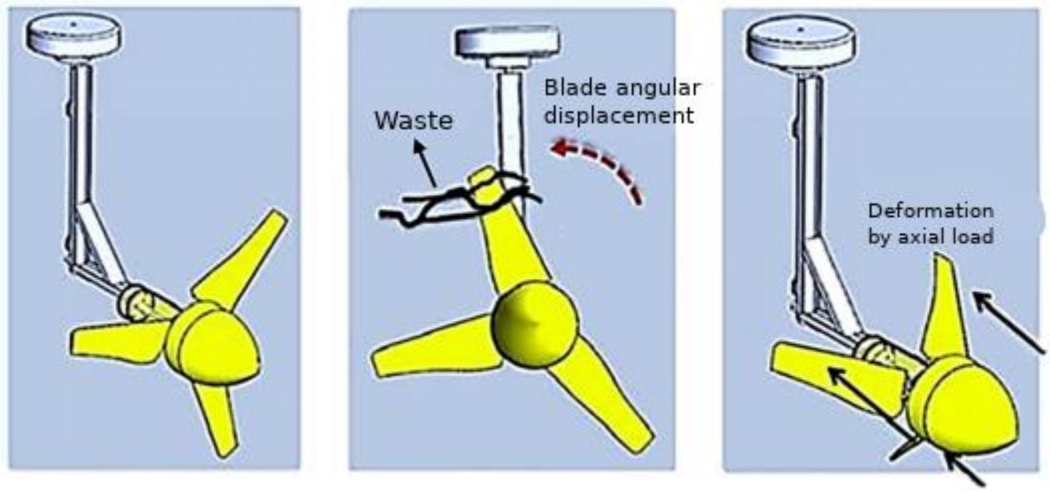

Figure 6. Hydrokinetic turbine operations: a) normal operation, b) capacity of the blade to move angularly on its axis of rotation, and c) ability to tilt the blades downstream of the turbine (Anyi & Kirke, 2015).

Use of diffusers or nozzles to increase the power generated by horizontal shaft hydrokinetic turbines

One of the ways to improve the power generated by THCEH is to use diffusers and/or nozzles. A diffuser increases the pressure of the fluid by decreasing its speed, while the nozzles perform the opposite function. All this, seeking to improve circulation and reduce the stagnation of the fluid downstream of the turbine (Chen, Ponta, & Lago, 2011). An important factor to take into account is that the implementation of these diffusers makes it possible to increase the power coefficient of the THCEH (Chen *et al*., 2011; Chen, Liao, & Cheng, 2012; Gaden & Bibeau, 2010). The main problem with the diffusers is the pressure drop generated at the outlet by the extraction of energy from the turbine inside the duct. Therefore, this type of system uses a convergent section with a relatively small angle of inclination at the front of the canal, and a divergent section with a steeper exit angle at the rear of the canal (Chen *et al*., 2011).

To counteract the low power density generated by a THC, Gaden and Bibeau (2010) performed a numerical study that analyzed the use of diffusers in order to improve the performance and viability of the THCEH. With the proposed diffuser they obtained up to 3.1 times more power compared to a turbine without this element.

A similar analysis was carried out by Shahsavarifard *et al*. (2015), in which three models were evaluated experimentally: the first was a THCEH, the second was also a THCEH but with an external cover, and the third was a THCEH with a diffuser. The result was a 91% improvement in the maximum output power of the third model with respect to the first. The literature reflected great interest in the implementation of diffusers, where many of the improvements that have been developed have to do with their shape, especially at the entry and exit areas (Chen *et al*., 2011; Chen *et al*., 2012).

Therefore, a wide field of study in this area has been presented, since there is still a great variety of diffuser profiles to be analyzed and even more with respect to hydrokinetic turbines, given that a large part of the investigations carried out have been about wind turbines.

Arrangement in water of horizontal axis hydrokinetic turbines

Several investigations found in the literature focused on different ways of distributing the THCEH in rivers, seas, channels, or any other medium in which they will operate or be analyzed. These include the individual arrangement of the THCEH, which is the most common distribution, as well as serial configurations of several of these, which increases the power generated by the system, or ensures optimal operating conditions. Filho *et al*. (2010) proposed a system of THCs called Poraquê, which consists of horizontal axis hydrokinetic turbines arranged in series along the same axis, spaced and positioned in such a way that there is no interference between rotors. This was analyzed by means of an artificial canal. The authors found an efficiency of 78% when using 3 turbines (with diameters of 1.5 m) at a distance between them of 710 mm. They also pointed out that using a greater number of blades is not feasible since it results in little increased efficiency as compared to the cost of manufacture and assembly, and offered some ideas to improve the system, such as the use of diffusers to direct and recover the speed of the flow. Investigations that could complement the previous study were found, such as the study by Neary, Gunawan, Hill and Chamorro (2013) who analyzed the perturbations in the wake of the turbine, finding that 80% of the recovery of the flow occurred close to 10 diameters downstream from the rotor plane, depending on the size of the turbine. This also suggests that the spacing between THCEH be between 10 and 15 rotor diameters. Meanwhile, Kolekar, and Banerjee (2015) studied the proximity effect of the edges of hydrokinetic turbines in shallow channels, finding that to obtain optimum performance, these must be installed in such a way that the rotating disk is at a minimum distance from the solid wall of the channel (equivalent to a rotor radius) and with a minimum water depth greater than 3.5 times the radius of the turbine.

Conclusions

The studies carried out on hydrokinetic turbines show that this is a young technology with a large field of application, which can be used to supply electricity to areas that have nearby water sources without the need for falls or water heights, making this an alternative requiring little financial investment, and which is affordable and easy for the population to maintain, who are generally in isolated areas and have little income and an adequate quality of life.

The field of research on hydrokinetic turbines is broad, since the studies carried out have been based on the adaptation of analyses and results from wind turbines, and the technology is in a trial-and-error stage. There is still a large number of hydrodynamic profiles to be analyzed, in addition to the implementation of various improvements and modifications made to wind mechanisms in order to increase the efficiency of hydrokinetic turbines.

There is evidence of growing confidence in the use of computational simulations to analyze the hydrodynamics and structures of hydrokinetic turbines, enabling them to be more easily optimized, greatly reducing manufacturing costs.

There is a great tendency to use diffusers in order to improve the efficiency of hydrokinetic turbines. And one of the major problems with this technology is the debris, weeds, and other foreign elements present in the rivers. These are two interesting starting points that can be addressed by future studies on hydrokinetic turbines.

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