International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 14, Number 7 (2021), pp. 708-716

Vertical axis Darrieus turbines: State of the art research

José D. Cardona Cárdenas[1], Juan G. Ardila Marín[2], Jhony M. Gutiérrez Flórez[3] and Carlos A. Ramírez Vanegas[4]

[1] *M.En., Student, Industrial Energy Management, Instituto Tecnológico Metropolitano, Medellín (Colombia).*

[2] *Assistant Professor, Agricultural Engineering Program, Universidad Surcolombiana, Neiva (Colombia).*

[3] *Occasional Professor, Mechanical Department, Institución Universitaria Pascual Bravo, Medellín (Colombia).*

[4] *Assistant Professor, Mathematics Department, Universidad Tecnológica de Pereira, Pereira (Colombia). caramirez@utp.edu.co*

Abstract

The generation of electrical energy from non-conventional renewable sources such as wind and minihydro has become an important alternative for the satisfaction of human needs in a sustainable and environmentally friendly way, for this reason, the development of appropriate technologies and efficient that allow such generation is essential. Darreius type turbines have been studied for their application in the use of the mentioned sources. The present work sought to identify the main objectives that have motivated the work of researchers around the world over the years and with recent emphasis, to report the main applied research methodologies and the most relevant results, such that they can guide the future research work. The systematic review was organized according to the most investigated factor, which was the power coefficient (efficiency) of the turbines, and according to the parameters that were identified as having the highest incidence in said coefficient, starting with the geometric factors. The configuration of numerical studies, mainly with computational fluid dynamics (CFD), and of the experimental studies that were reviewed were described in some detail. It is expected that this work will serve as a starting point for research projects that promote the development and implementation of technologies of this type in the use of energy from available sustainable sources.

Keywords: Fluid Mechanics, Renewable Energy, Turbomachinery, Hydraulic Turbines.

I. INTRODUCTION

The speed produced by the current of water carried by a river provides a great source of kinetic energy that can be used to generate electrical energy. That is why different types of turbomachines known as submerged hydrokinetic turbines have been developed that take advantage of this resource. These developments have occurred due to the need of some remote areas that do not have a supply system or interconnection to a national network. Hydrokinetic turbines allow the flow to pass through the rotor by means of a set of blades, which cause the kinetic energy to generate a torque in the turbine rotor, limiting the passage of the fluid in a single direction [1]. The relative speed is presented due to the variation between the absolute speed of the fluid and the speed of impact on the blade, this relationship is defined as TSR (Tip Speed Ratio or λ) also known as the "Tip speed ratio". It is important to mention that the energy of the fluid that passes through the turbine is not used 100%, that is why a power coefficient has been defined that indicates the amount of kinetic energy that can be extracted from the flow and converted into energy. mechanical flow through the rotor, a limit known as the Betz limit [2] is imposed on this coefficient, which determines that the maximum utilization value is 59.3%.

After a decline in interest in the 1990s, research on vertical axis turbines has reappeared in recent years as a result of their increasing application in the environment, where they have several advantages over the horizontal axis [3]. The Darrieus turbine was initially developed for the use of wind energy, after which studies have been carried out for its application in the conversion of hydrokinetic energy, with the aim of establishing its implementation, since until now they have only been applied in channels or small tributaries [4]. Shiono et al., (2000) developed a study on the characteristics of the Darrieus turbine where their main interest was the effect of solidity, which is defined as the relationship between the number of blades and the rotor radius, being the ideal parameter To characterize the size of the turbine, the diagram of the turbine evaluated in said study is shown in Figure 1 to illustrate the general geometric arrangement of this type of turbines. The turbine was tested in controlled channels in order to find the most suitable values for the robustness of the rotor, where its efficiency (power coefficient) is related to the characteristics of the water stream, the torque generated in the rotor and its speed angular.

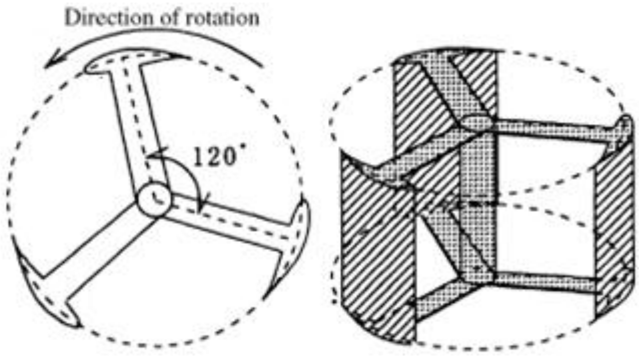

Fig. 1. Darrieus hydrokinetic turbine: General arrangement [4].

The generation of kinetic energy using the flow of rivers has promoted the study and use of Darrieus turbines, however, the limitations of auto starting and the low power coefficient create potential for improvement. This article presents the results of the most relevant research carried out on the technology and use of Darrieus-type hydrokinetic turbines, starting by detailing the discussions on their geometry and the generation of mechanical power on their shaft, and culminating with the distinction between numerical and experimental methodologies used in their study.

II. GEOMETRY OF DARRIEUS TYPE TURBINES

The first parameter to take into account is the aerodynamic profile, Yurdusev et al., (2006) said that the key to designing a Darrieus type turbine is to evaluate the optimal relationship between its TSR and its power coefficient, for this optimization they used networks Artificial Neural Networks (ANN - Artificial Neural Networks) based on the parameters involved for the types of aerodynamic profile with which they designed their blades: NACA 4415 and LS-1, considering also important the evaluation of the number of blades and, in general, the robustness of the rotor, thus they studied with 3 and 4 blades [5]. In 2011, Batista et al., proposed the EN0005 blade profile with divided surface for the Darrieus vertical axis turbine, such that it could start by itself at low speeds, developing a methodology to compare it with other profiles. known, since the biggest design drawback reported for this type of turbine was self-start. The prototype presented a low rotation speed, where the torque was its main impediment when working at low wind speeds, having a stable behaviour at a speed of 1.25 m/s, which means that although it does not need a starter to help the turbine, it does not achieve a higher torque compared to starter-assisted turbines. It should be noted that both studies were developed for wind turbines [6].

Darrieus H-type rotor turbines, although they have a good power coefficient, have a deficiency in their automatic start-up because most of the time symmetrical blade profiles are used, which is why Sengupta et al., (2016) studied the implementation of non-symmetrical or curved blades with high solidity, which managed to improve the starting performance of the H-Darrieus rotor together with its power coefficients. They considered three profile models the S815, EN0005 and a conventional symmetric blade NACA 0018 as seen in Figure 2, with wind currents of (4 m/s, 6 m/s and 8 m/s), obtaining as a result that S815 non-symmetrical profile rotor has higher dynamic torque and power coefficient than EN0005 profile rotor, and the coefficients of NACA 0018 symmetrical profile rotors are much lower in comparison, depending on the operating conditions in the study [7].

Brusca et al., (2015) studied the conversion of hydraulic energy through a Darrieus turbine with 5 blades designed with the NACA 0012 profile, modelled the phenomenon numerically and validated it by building a scale model [8]. Marsh et al., (2015) made three turbine designs as shown in Figure 3, using two types of profiles: the NACA0012 and the mechanized flat bar proposed by them, making 3D models and after them the CFD simulation using the unstable Reynolds averaged model (URANS) based on the Navier-Stokes model; determined that the section of the chord and the design of the connection between the arm of the structure and the blade significantly influence the power output generated by the turbine [9]. Kumar et al., (2017) to improve the performance of the turbine, incorporated a KF-N-21 notched aerodynamic profile in a Darrieus rotor, comparing it with the NACA 0021 profile, showing that this profile has a good performance with a wide range of Reynolds numbers, which indicates that it can be subjected to quite high turbulence patterns and allows to obtain good results in terms of generated torque [10]. Another parameter, associated with the profile, that affects performance is the length of the chord [11].

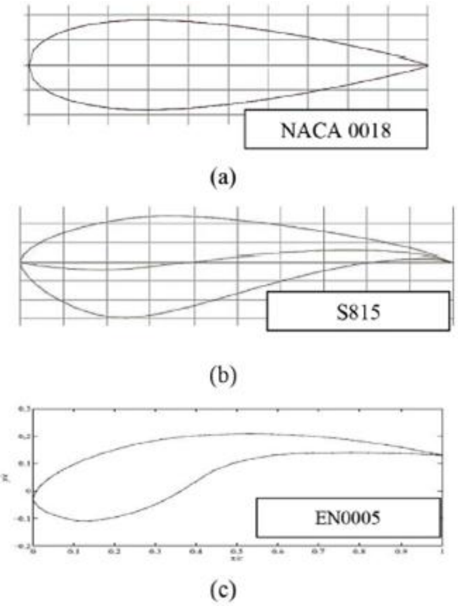

Fig. 2. Aerodynamic profiles of the blade: Symmetric - a) NACA 0018, and Non-Symmetric - b) S815 and c) EN005, studied by Sengupta et al., (2016) [7].

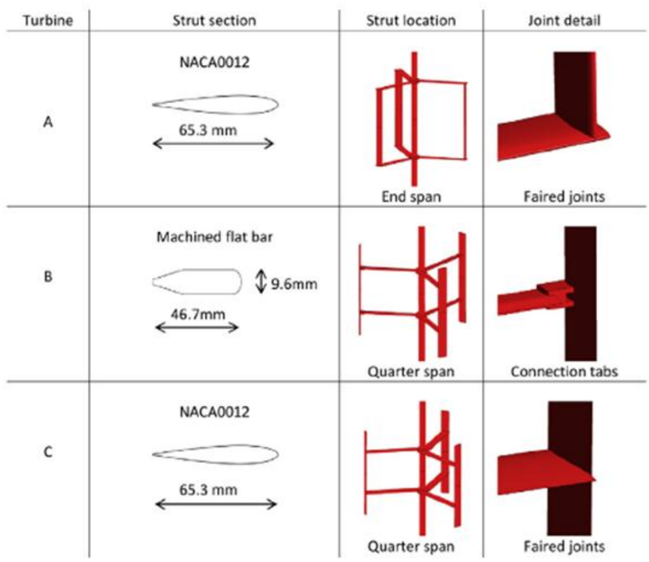

Fig. 3. Section of the Darrieus turbines studied by Marsh et al., (2015) with profile and connection detail [9].

Gosselin et al., (2016) investigated via CFD that, in addition to the parameters, the angle of inclination of the blade also has an impact on the power generation of the turbine. Angle of attack is formally defined as the angle between the chord of the air foil and the direction of flow away from the profile. In their study they found that the blades of a turbine operating at low TSR encounter much higher angles of attack than a turbine operating at high TSR [12].

III. DESIGN AND OPERATION OF DARRIEUS TURBINES

The rotor of the Darrieus turbines is a fundamental part for the optimization of the operation of the same [13]. Ikoma et al., (2008) investigated the hydrodynamic forces in a fixed blade with various angles, all this developed numerically and experimentally, concluding that by setting the angle of the blade they control the operation of the torque [2]. Qamar & Janajreh, (2017) carried out a study that showed that low-strength turbines with curved blades have low power coefficients in a wide range of TSR, while high-strength turbines, with a strength close to unity, have a coefficient much higher, but at smaller TSRs and a narrow range [14]. Lee & Lim, (2015) studied the performance of the Darrieus type turbine in its torque and power characteristics, focusing on the optimal design of the blade shape, showing few disturbances and interactions with the ambient flow [11].

Overall, although the NACA profile had significant changes in lift and breakout force with respect to angle of attack, the use of a longer chord length and a smaller head diameter (i.e., greater strength) increased the performance of power as a function of TSR.

Jafari et al., (2018) carried out a study on the aerodynamic performance of six profiles S809, S814, RISØ-A1-24, Du 93-W-210, FFA-W3-241 and FX66-S196-V1 of the turbine of vertical axis of Darrieus type rotor. To verify performance, the results were compared with the experimental data for the NACA0012 profile. For the FFA-W3-241 aerodynamic profile, the maximum power coefficient was obtained with a solidity of 0.5 and a top speed ratio of 4, resulting in an increase of 22.4% and 21.9% in the Energy production [15]. Çetin et al., (2005) studied the optimal speed in relation to the profile used and the number of blades, since this directly affects the power generation of the turbine [1]. Xiao et al., (2013) studied the impact on efficiency improvement with the use of turbine energy by using fixed and oscillating blades with a NACA0018 profile as a reference. The results obtained under optimal flow and geometry conditions showed that the power coefficient improves by 28% compared to the conventional blade turbine [16].

The characteristics of the flow have been carefully investigated according to the relationships between TSR and fastness, increasing the fastness alone does not improve the performance of Darrieus type turbines. On the one hand, the decrease in robustness can reduce the blocking effect, but the automatic start characteristics at low TSR are lost. On the other hand, a comparison of the aerodynamic characteristics in various operating conditions, using a dual-flow tube model, was carried out to predict the performance of turbines with high robustness [17]. Tunio et al., (2020) studied the effect of the straight blade and the interaction between the fluid and the turbine structure, through CFD applying shear stress transport models (SST). Concluding that the speed of rotation at free flow speed has an energy production of 112% compared to the systems of channels of controlled flow speed, but the efforts generated in the rotor are higher, thus increasing the cost of the material of the turbine [18].

Liang et al., (2017) studied the performance and efficiency by means of CFD with the k-ε turbulence model, where they tested various configurations and relationships between the angle of attack and the chord length of the Darrieus - Savonius combined rotor, obtaining as The combined rotor configuration resulted with a maximum power coefficient of 0.363 and a starting torque below 0.1 Nm at a speed of 2 m/s [19]. Shimizu et al., (2016) built an improved prototype of the hydraulic turbine with a NACA 63 3-018 profile capable of generating 1.4 W with a flow velocity of 1 m/s where it is possible to start automatically. Considering reality, they also studied the effects of flow non-uniformity and turbulence intensity on rotor performance under optimal conditions, as well as on flow physics [20]. Abdalrahman et al., (2017) studied the control of the angle of inclination of the blade to improve the performance of the Darrieus vertical axis turbine with respect to the power output, using ANSYS® CFD to determine the angle of inclination with respect to different TSR [21].

The characteristics of the material of the turbine blades and the interaction with the fluid have become an important object of study. That is why Hoerner et al., (2019) studied the oscillation parameters and the TSR, both for a rigid blade and for three flexible blades with different stiffness. Using a model consisting of an oscillating blade NACA0018 in a closed water channel, following a law of motion comparable to the actual angle of incidence of a Darrieus turbine blade throughout its rotation [22].

On the other hand, Hashem & Mohamed, (2018) investigated the performance of three types of diffuser (flat panel, curved surface and cycloidal surface) as shown in Figure 4, evaluated in 24 classes of straight profiles of the Darrieus turbine to improve the power generated for a flow velocity that varies from 2 to 7 m/s, showing that the S1046 profile has better performance. Obtaining as a result that a turbine equipped with a cycloidal diffuser has a power increase of 3.9% compared to a conventional Darrieus turbine [23]. Mohamed et al., (2019) investigated the aerodynamic and acoustic characteristics of the Darrieus rotor, its scope reached the performance and then evaluated the amount of noise achieved with the improvement of the inclusion of diffusers. Optimal design parameters are achieved with diffusers and in its optimized configuration it shows an increase in generated power and power coefficient of approximately 82% at a TSR of 2.75. However, the noise increases with these diffusers [24].

About the starting problem, variable bank angle approaches are one of the best strategies to improve the performance and self-starting ability of Darrieus turbines and delay the onset of dynamic stall phenomena. Sagharichi et al., (2019) analysed the relationship between the angle of attack and the automatic start performance of the H-type vertical axis wind turbine, with four attack angles 0 °, 3 °, 10 ° and 20 ° and the model was developed via CFD simulation, obtaining as a result that the 0 ° angle of attack could reduce the time required for the rotor to start and obtain a 34% increase in the power generated [25].

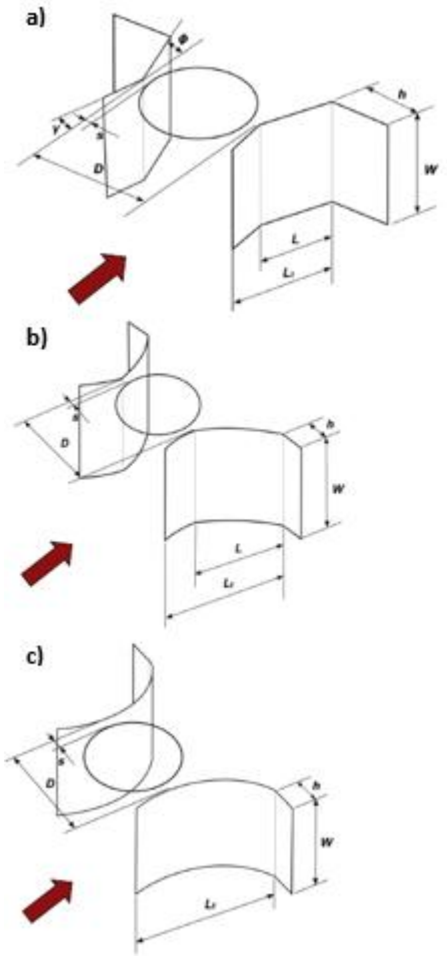

Fig. 4. a) Flat panel diffuser, b) curved surface and c) cycloidal surface [23].

Mohamed et al., (2020) studied the low starting torque of the Darrieus type turbine, using a slotted profile NACA0018 to improve it, as well as its performance characteristics, managing to improve the ability to generate a higher torque at low speeds compared to other profiles. So, the analysis showed that the slotted profile improves the torque and power coefficient at low TSR [26]. Asr et al., (2016) developed a study via simulation to reduce the turbine start-up time by making variations in the profile of the blade, using the NACA 2418 profile with an outward inclination angle of 1.5 °, they obtained a decrease at the rotor start-up time while maintaining maximum turbine performance [27].

In relation to multiple turbine arrangements, Antheaume et al., (2008) performed simulations combining the Navier-Stokes calculation of the external flow and the internal flow around the turbine, this model is used for an arrangement of several turbines to determine their efficiency, and the results showed that it increases as the distance between turbines decreases [28]. Malki et al., (2014) studied a CFD coupled blade element momentum model (BEM-CFD) for groups of turbines, analysing the effects of separation and position of the turbines with respect to the flow dynamics and performance of the rotor. Staggered turbine configuration and proper rotor spacing can achieve more than 10% power output increase over traditional configuration [29].

IV. CFD STUDIES OF DARRIEUS TURBINES

Computational fluid dynamics is believed to provide an essential contribution to the development of vertical axis turbines soon [30]. The Darrieus rotor has gained much interest in recent decades as one of the reliable devices for energy conversion techniques due to its relatively simple structure and aerodynamic performance [31]. Bianchini et al., (2017) carried out a comparison between experimental data and simulations, having simplifications with the 2D simulation, this managed to provide quite accurate estimates both in the performance and in the flux around the rotor under suitable configuration conditions, since the collected data show a variation between them of less than 10%, and there was a great saving of computational resources [32].

Balduzzi et al., (2016) studied the behavior at different TSRs (1.7, 2.2, 3.3 and 4.4) to determine the optimal mesh sizes and simulation times, having to guarantee an accurate description of the velocity gradients in the surrounding region. to the blade, using 4 different TSR [33]. Mohamed et al., (2019) focused their studies on determining the performance of the three-blade Darrieus turbine using 25 different profiles, until optimization using CFD computational tools, finding an agreement between the numerical and experimental results, the Turbine power coefficient with LS profile (1)-0413 increased by 16% compared to the performance of NACA 0021 [24].

López et al., (2016) studied the behaviour of the vertical axis Darrieus turbine, with emphasis on the analysis of the hydrodynamic characteristics, for this they defined a turbine with a rotor diameter of 900mm and three blades with a chord size of 132 mm, in addition, they defined three domains: 2 static domains and 1 rotary ring type where the blades meet, being the one of greatest interest. These domains were discretized in the GAMBIT® software making a greater refinement in the area of the blades, to then be taken to the Fluent® ANSYS® program studying different turbulence models and as a result the behavior and production of turbine torque during one turn, in addition, they investigated the influence of the lock ratio, the geometry of the trailing edge of the profile and the selected turbulence models in the prediction of the turbine performance [34].

Dai & Lam, (2009) studied the design of a Darrieus turbine using a time-averaged K-ω turbulence model with Reynolds [35], Lain & Osorio, (2010) simulated a 3 blades; the developed model was able to effectively predict the hydrodynamic performance of a vertical axis turbine [36]. Lanzafame et al., (2014) demonstrated the good capacity of the Transition SST turbulence model in comparison with the classic turbulence models. The 2D CFD model was validated by comparing the results with two different types of experimental data available in the literature [37]. Wang et al., (2010) studied the unstable flow around a NACA0012 profile with low Reynolds number (Re = 105) using 2D CFD, crossing these results with experimental data provided by the literature, the simulation results agree, except when the profile has a very high angle of attack [38].

Lam & Peng, (2016) studied wake velocity and turbulence field in a low solidity vertical axis turbine, using the Navier-Stokes model to examine the wake velocity field and turbulence field at positions of 1D to 10D, with the result that the wake close to 3D the wind speed suffered a deficit of 85%, while at 10D it reached an average speed of 75% compared to the other speeds [39].

Maître et al., (2013) worked on the evaluation of the dimensionless mesh parameter known as y+ (dimensionless wall distance) that affects a 2D Darrieus turbine and they worked on finding the maximum acceptable value, where the specification is not known exact y+, and its influence on either the overall turbine or fluid performance for various turbulence patterns [40].

On the other hand, Zamani et al., (2016) studied the J-shaped blade to know the power generated via simulation, their CAD model can be seen in Figure 5. The combined forces help the turbine to have a faster operation at low TSR. The NACA0015 profile is served as a base and has been modified to generate the desired J-shape profile. The results obtained indicate improvements in the torque and power coefficients, more specifically in the first half of the revolution, that is, $0° < \theta < 180°$ [41].

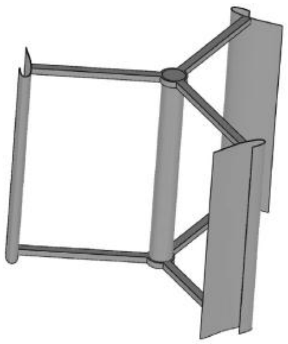

Fig. 5. Darrieus turbine with vertical axis in the shape of a "J" [41].

Table 1 aims to summarize the main configuration parameters of some relevant numerical studies for the case of hydraulic application, to compare the wide ranges of research that have been covered using this valuable tool.

In Table 1 several findings are evident, the first is the, already mentioned, increase in world interest in the study of this technology applied to the use of energy from water flows, the second is the generalized use of the turbulence model k-omega SST in numerical investigations, the third is the predominant use of 3 blades, and associated with this and the ranges of rotor diameters and chord lengths evaluated, there is a tendency to decrease the solidity studied, remaining lower to unity. The ranges of flow velocities vary from very low river velocities, characteristics of low slopes, to average velocities typical of mighty rivers in stretches of wide section, it is noted that there is no interest in rapids that are experienced in narrow sections of rivers or rivers. steep slope, where speeds can reach or exceed 2.5 to 3 m/s; Even so, certainly variable TSR ranges have been evaluated, it is difficult to establish a characteristic operating range, obviously in these ranges an inverted parabola behavior has been evidenced in the turbine performance curve, reporting maximum power coefficients in the range Expected between 0.2 and 0.35, reported findings of high efficiencies such as 0.42 or 0.45 are surprising, but a report of 0.6 that exceeds the Betz limit is strange. Certainly, the hydrodynamic profile of the blades has aroused the interest of research, but the study of profiles NACA0018 and 0025 is recurrent, which were the first profiles proposed, but later many revolutionary alternatives have been introduced and have become a trend in the research of this technology.

V. EXPERIMENTAL STUDIES OF DARRIEUS TURBINES

Han et al., (2013) investigated the characteristics of a vertical axis turbine based on a field test. After installing 2.2 and 3.0 m diameter helical turbines in a fast and narrow channel off the coast of Korea, they measured rotational speed and power. With the results that the efficiency of the 2.2 m diameter helical turbine was approximately 30% at flow speeds between 1.5 m/s and 1.9 m/s, and the 3.0 m diameter turbine diameter reported an efficiency of 33% at a flow velocity of 2.0 m/s to 3.4 m/s. Concluding that an energy generating system that uses tidal current as flow can produce electrical energy in a stable way as long as the flow speed is appropriate [42].

Singh et al., (2015) carried out an experimental investigation of 3 profiles (NACA 0012, S1046 and S1210) focusing on the S1210 profile, varying its robustness and input speed for high efficiency and auto start analysis and reached the conclusion that this profile presents a maximum power coefficient of 0.32 at the moment of having a solidity of 1.0 with a wind speed of 5.7 m / s, in addition the static torque coefficient is four times greater than the turbine with symmetrical (NACA 0012) and asymmetric (S1046) blade [43].

As a solution to the disadvantage that Darrieus turbines have when starting, Kumar et al., (2017) propose a double rotor turbine as seen in Figure 6, to improve starting and low speed performance. The design parameters for the secondary rotor, such as robustness, adequate airfoil, diameter of the secondary rotor, displacement of the secondary rotor with respect to the primary rotor, require great optimization, taking this study as a starting point [44].

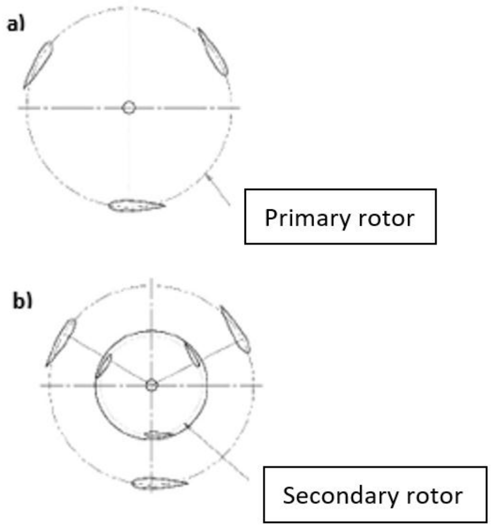

Fig. 6. a) Primary rotor, b) Secondary rotor. Adapted from Kumar et al., (2017) [44].

Table 1. Summary of relevant hydraulic numerical studies.

Reference	TSR	Vel. [m/s]	Solidity	# Blades	Rotor Diameter [mm]	Chord Length [mm]	Profile Type	Turbulence model	CP max.
[35]		0.99-1.62	0.59-1.64	3	597.8-900	88.2-162.88	NACA 0025 y 0018	K-w (SST)	
[9]	1.5-3.5	1.5		3	914	65	NACA63-021	K-w (SST)	0.25
[34]	1.25-2.3	1.62	0.89	3	900	132.75	NACA0025, 2415 y 4415	K-w (SST)	0.35
[20]		0.5-1	0.2-0.291	3-4		200	NACA 63 3-018		0.3
[45]	0.0-1.6		0.258-0.434	3	220-370		NACA 0015, 0018 y 4415		0.2
[46]	0.8-2.4	1.5	0.38	3	300	119	NACA0010, 0018 y S-1046, 9000	K-w (SST)	0.42
[47]		0.389	0.18	3	265	50	NACA0018		0.35
[48]	1.4-5.7	1.58	0.2	3	450	94	S-1046	K-w (SST)	0.3
[18]	1.88-8.79	0.2-1.4		3	1500	200	NACA0020	K-w (SST)	
[49]	1.8-5.0	1.58	0.13-0.26	3	450	118.5	NACA0018, S-1046, 809 y FXLV152		0.3

Patel et al., (2017) carried out experiments to evaluate four types of rotors with symmetric profile NACA0018 and cambo-NACA4415, making variations in solidity from 0.258 to 0.434, concluding that the minimum distances of 7D along the direction of the flow and 3D along the transverse direction are essential when using Darrieus turbines. Subsequently, (Patel et al., 2019) studied the performance of a Darrieus turbine using a locking plate optimally located on the upstream side of the retarding fin. Three locking plates (75mm wide, 100mm wide and 170mm wide) are investigated for five different locations, and the turbine power coefficient is improved from 0.125 to 0.36 through the optimal use and placement of lock plate [45].

VI. CONCLUSION

Very relevant research works about vertical axis wind and hydrokinetic turbines of the Darrieus type were reviewed. It was identified that the main research results are oriented to the power coefficient that gives an idea of the efficiency that the devices will have in converting hydraulic energy from a flow into mechanical energy in the rotor shaft of the turbine, which could later become electrical energy for consumption. And it was established that of the multiple parameters that affect the power coefficient, the most evaluated are the TSR, which is related to the flow conditions that could be experienced at the implementation site, and, in turn, with geometric parameters that are also widely evaluated, including robustness, which refers to the size of the turbine in terms of rotor diameter and number of blades, and the aerodynamic or hydrodynamic profile, depending on the application studied. In addition, other geometric and constructive parameters that can affect the efficiency of the Darrieus type of turbines are reported and have also been studied.

On the other hand, the most common research methodologies have been reported in the identified studies, found numerical modelling tools applied to solve optimization and simulation problems of physical phenomena such as, for example, turbulent flows that are experienced around the blades. in the rotor and are associated with energy conversion, and, in addition, experimental studies that have validated the numerical results, and multiple studies that combine both strategies. In general, the configurations of some studies were described, such that they serve to guide future research on this important topic.

The idea of implementing this type of turbine to acquire hydraulic energy is interesting, drawing the attention of many researchers due to its characteristics, operation and performance, which make it an alternative for the use of natural resources, since its implementation is easy. due to its low cost, somewhat simple construction and useful for use in conditions of low flow velocities. It is necessary to generate energy solutions that are friendly and clean in relation to the environment and whose implementation is easy and low cost, these solutions allow to contribute to the increase in the generation capacity of clean energy, which in turn satisfies the energy needs of the communities, especially those that are geographically isolated, which makes it difficult to connect interconnected systems. For this reason, hydrokinetic turbines aim to be a clean and environmentally friendly solution as well, due to their easy construction and cost of implementation, thus satisfying the energy needs of a large part of the world's population. For this reason, it is proposed, as a step to follow, the numerical evaluation of the behaviour of a 100-watt H-Darrieus type hydrokinetic turbine that allows the use of hydraulic resources in non-interconnected areas of Colombia.

REFERENCES

[1] N. S. Çetin, M. A. Yurdusev, R. Ata, and A. Özdemir, “Assessment of optimum tip speed ratio of wind turbines,” *Math. Comput. Appl.*, vol. 10, no. 1, pp. 147–154, 2005, doi: 10.3390/mca10010147.

[2] T. Ikoma, K. Masuda, S. Fujio, H. Nakada, H. Maeda, and C. K. Rheem, “Characteristics of hydrodynamic forces and torque on Darrieus type water turbines for current power generation systems with CFD computations,” *Ocean. MTS/IEEE Kobe-Techno-Ocean’08 - Voyag. Towar. Futur. OTO’08*, 2008, doi:

10.1109/OCEANSKOBE.2008.4531094.

[3] C. S. Ferreira, G. Van Bussel, and G. Van Kuik, "2D CFD simulation of dynamic stall on a vertical axis wind turbine: Verification and validation with PIV measurements," *Collect. Tech. Pap. - 45th AIAA Aerosp. Sci. Meet.*, vol. 23, no. January, pp. 16191–16201, 2007, doi: 10.2514/6.2007-1367.

[4] M. Shiono, K. Suzuki, and S. Kiho, "Experimental study of the characteristics of a Darrieus turbine for tidal power generation," *Electr. Eng. Japan (English Transl. Denki Gakkai Ronbunshi)*, vol. 132, no. 3, pp. 38–47, 2000, doi: 10.1002/1520-6416(200008)132:3<38::AID-EEJ6>3.0.CO;2-E.

[5] M. A. Yurdusev, R. Ata, and N. S. Çetin, "Assessment of optimum tip speed ratio in wind turbines using artificial neural networks," *Energy*, vol. 31, no. 12, pp. 2153–2161, 2006, doi: 10.1016/j.energy.2005.09.007.

[6] N. C. Batista, R. Melício, J. C. O. Matias, and J. P. S. Catalão, "New blade profile for darrieus wind turbines capable to self-start," *IET Conf. Publ.*, vol. 2011, no. 579 CP, 2011, doi: 10.1049/cp.2011.0219.

[7] A. R. Sengupta, A. Biswas, and R. Gupta, "Studies of some high solidity symmetrical and unsymmetrical blade H-Darrieus rotors with respect to starting characteristics, dynamic performances and flow physics in low wind streams," *Renew. Energy*, vol. 93, pp. 536–547, 2016, doi: 10.1016/j.renene.2016.03.029.

[8] S. Brusca, F. Cucinotta, A. Galvagno, R. Lanzafame, S. Mauro, and M. Messina, "Oscillating Water Column Wave Energy Converter by means of straight-bladed Darrieus turbine," *Energy Procedia*, vol. 82, pp. 766–773, 2015, doi: 10.1016/j.egypro.2015.11.809.

[9] P. Marsh, D. Ranmuthugala, I. Penesis, and G. Thomas, "Three-dimensional numerical simulations of straight-bladed vertical axis tidal turbines investigating power output, torque ripple and mounting forces," *Renew. Energy*, vol. 83, pp. 67–77, 2015, doi: 10.1016/j.renene.2015.04.014.

[10] P. M. Kumar, M. M. R. Surya, and N. Srikanth, "On the improvement of starting torque of darrieus wind turbine with trapped vortex airfoil," *2017 IEEE Int. Conf. Smart Grid Smart Cities, ICSGSC 2017*, pp. 120–125, 2017, doi: 10.1109/ICSGSC.2017.8038561.

[11] Y. T. Lee and H. C. Lim, "Numerical study of the aerodynamic performance of a 500W Darrieus-type vertical-axis wind turbine," *Renew. Energy*, vol. 83, pp. 407–415, 2015, doi: 10.1016/j.renene.2015.04.043.

[12] R. Gosselin, G. Dumas, and M. Boudreau, "Parametric study of H-Darrieus vertical-axis turbines using CFD simulations," *J. Renew. Sustain. Energy*, vol. 8, no. 5, 2016, doi: 10.1063/1.4963240.

[13] M. J. Khan, M. T. Iqbal, and J. E. Quaicoe, "Design considerations of a straight bladed darrieus rotor for river current turbines," *IEEE Int. Symp. Ind. Electron.*, vol. 3, no. 2, pp. 1750–1755, 2006, doi: 10.1109/ISIE.2006.295835.

[14] S. B. Qamar and I. Janajreh, "A comprehensive analysis of solidity for cambered darrieus VAWTs," *Int. J. Hydrogen Energy*, vol. 42, no. 30, pp. 19420–19431, 2017, doi: 10.1016/j.ijhydene.2017.06.041.

[15] M. Jafari, A. Razavi, and M. Mirhosseini, "Effect of airfoil profile on aerodynamic performance and economic assessment of H-rotor vertical axis wind turbines," *Energy*, vol. 165, pp. 792–810, 2018, doi: 10.1016/j.energy.2018.09.124.

[16] Q. Xiao, W. Liu, and A. Incecik, "Flow control for VATT by fixed and oscillating flap," *Renew. Energy*, vol. 51, pp. 141–152, 2013, doi: 10.1016/j.renene.2012.09.021.

[17] S. Joo, H. Choi, and J. Lee, "Aerodynamic characteristics of two-bladed H-Darrieus at various solidities and rotating speeds," *Energy*, vol. 90, pp. 439–451, 2015, doi: 10.1016/j.energy.2015.07.051.

[18] I. A. Tunio, M. A. Shah, T. Hussain, K. Harijan, N. H. Mirjat, and A. H. Memon, "Investigation of duct augmented system effect on the overall performance of straight blade Darrieus hydrokinetic turbine," *Renew. Energy*, vol. 153, pp. 143–154, 2020, doi: 10.1016/j.renene.2020.02.012.

[19] X. Liang, S. Fu, B. Ou, C. Wu, C. Y. H. Chao, and K. Pi, "A computational study of the effects of the radius ratio and attachment angle on the performance of a Darrieus-Savonius combined wind turbine," *Renew. Energy*, vol. 113, pp. 329–334, 2017, doi: 10.1016/j.renene.2017.04.071.

[20] S. Shimizu *et al.*, "Starting system for darrieus water turbine of tidal stream electricity generation," *Proc. Int. Conf. Offshore Mech. Arct. Eng. - OMAE*, vol. 6, pp. 3–8, 2016, doi: 10.1115/OMAE2016-55143.

[21] G. Abdalrahman, W. Melek, and F. S. Lien, "Pitch angle control for a small-scale Darrieus vertical axis wind turbine with straight blades (H-Type VAWT)," *Renew. Energy*, vol. 114, pp. 1353–1362, 2017, doi: 10.1016/j.renene.2017.07.068.

[22] S. Hoerner, S. Abbaszadeh, T. Maître, O. Cleynen, and D. Thévenin, "Characteristics of the fluid–structure interaction within Darrieus water turbines with highly flexible blades," *J. Fluids Struct.*, vol. 88, pp. 13–30, 2019, doi: 10.1016/j.jfluidstructs.2019.04.011.

[23] I. Hashem and M. H. Mohamed, "Aerodynamic performance enhancements of H-rotor Darrieus wind turbine," *Energy*, vol. 142, pp. 531–545, 2018, doi: 10.1016/j.energy.2017.10.036.

[24] M. H. Mohamed, A. Dessoky, and F. Alqurashi, "Blade shape effect on the behavior of the H-rotor Darrieus wind turbine: Performance investigation and force analysis," *Energy*, vol. 179, pp. 1217–1234, 2019, doi: 10.1016/j.energy.2019.05.069.

[25] A. Sagharichi, T. N. Ghaghelestani, and S. Toudarbari, "Impact of harmonic pitch functions on performance of

Darrieus wind turbine," *J. Clean. Prod.*, vol. 241, no. 2019, pp. 1–13, 2019, doi: 10.1016/j.jclepro.2019.118310.

[26] O. S. Mohamed, A. A. Ibrahim, A. K. Etman, A. A. Abdelfatah, and A. M. R. Elbaz, "Numerical investigation of Darrieus wind turbine with slotted airfoil blades," *Energy Convers. Manag. X*, vol. 5, no. November 2019, p. 100026, 2020, doi: 10.1016/j.ecmx.2019.100026.

[27] M. T. Asr, E. Z. Nezhad, F. Mustapha, and S. Wiriadidjaja, "Study on start-up characteristics of H-Darrieus vertical axis wind turbines comprising NACA 4-digit series blade airfoils," *Energy*, vol. 112, pp. 528–537, 2016, doi: 10.1016/j.energy.2016.06.059.

[28] S. Antheaume, T. Maître, and J. L. Achard, "Hydraulic Darrieus turbines efficiency for free fluid flow conditions versus power farms conditions," *Renew. Energy*, vol. 33, no. 10, pp. 2186–2198, 2008, doi: 10.1016/j.renene.2007.12.022.

[29] R. Malki, I. Masters, A. J. Williams, and T. Nick Croft, "Planning tidal stream turbine array layouts using a coupled blade element momentum - computational fluid dynamics model," *Renew. Energy*, vol. 63, pp. 46–54, 2014, doi: 10.1016/j.renene.2013.08.039.

[30] F. Balduzzi, A. Bianchini, R. Maleci, G. Ferrara, and L. Ferrari, "Critical issues in the CFD simulation of Darrieus wind turbines," *Renew. Energy*, vol. 85, pp. 419–435, 2016, doi: 10.1016/j.renene.2015.06.048.

[31] D. H. Didane, N. Rosly, M. F. Zulkafli, and S. S. Shamsudin, "Numerical investigation of a novel contra-rotating vertical axis wind turbine," *Sustain. Energy Technol. Assessments*, vol. 31, no. November 2018, pp. 43–53, 2019, doi: 10.1016/j.seta.2018.11.006.

[32] A. Bianchini, F. Balduzzi, P. Bachant, G. Ferrara, and L. Ferrari, "Effectiveness of two-dimensional CFD simulations for Darrieus VAWTs: a combined numerical and experimental assessment," *Energy Convers. Manag.*, vol. 136, pp. 318–328, 2017, doi: 10.1016/j.enconman.2017.01.026.

[33] F. Balduzzi, A. Bianchini, G. Ferrara, and L. Ferrari, "Dimensionless numbers for the assessment of mesh and timestep requirements in CFD simulations of Darrieus wind turbines," *Energy*, vol. 97, pp. 246–261, 2016, doi: 10.1016/j.energy.2015.12.111.

[34] O. López, D. Meneses, B. Quintero, and S. Laín, "Computational study of transient flow around Darrieus type cross flow water turbines," *J. Renew. Sustain. Energy*, vol. 8, no. 1, 2016, doi: 10.1063/1.4940023.

[35] Y. M. Dai and W. H. Lam, "Numerical study of straight-bladed Darrieus-type tidal turbine," *Proc. Inst. Civ. Eng. Energy*, vol. 162, no. 2, pp. 67–76, 2009, doi: 10.1680/ener.2009.162.2.67.

[36] S. Lain and C. Osorio, "Simulation and evaluation of a straight-bladed darrieus-type cross flow marine turbine," *J. Sci. Ind. Res. (India).*, vol. 69, no. 12, pp. 906–912, 2010.

[37] R. Lanzafame, S. Mauro, and M. Messina, "2D CFD modeling of H-Darrieus Wind Turbines using a transition turbulence model," *Energy Procedia*, vol. 45, pp. 131–140, 2014, doi: 10.1016/j.egypro.2014.01.015.

[38] S. Wang, D. B. Ingham, L. Ma, M. Pourkashanian, and Z. Tao, "Numerical investigations on dynamic stall of low Reynolds number flow around oscillating airfoils," *Comput. Fluids*, vol. 39, no. 9, pp. 1529–1541, 2010, doi: 10.1016/j.compfluid.2010.05.004.

[39] H. F. Lam and H. Y. Peng, "Study of wake characteristics of a vertical axis wind turbine by two- and three-dimensional computational fluid dynamics simulations," *Renew. Energy*, vol. 90, pp. 386–398, 2016, doi: 10.1016/j.renene.2016.01.011.

[40] T. Maître, E. Amet, and C. Pellone, "Modeling of the flow in a Darrieus water turbine: Wall grid refinement analysis and comparison with experiments," *Renew. Energy*, vol. 51, pp. 497–512, 2013, doi: 10.1016/j.renene.2012.09.030.

[41] M. Zamani, S. Nazari, S. A. Moshizi, and M. J. Maghrebi, "Three dimensional simulation of J-shaped Darrieus vertical axis wind turbine," *Energy*, vol. 116, pp. 1243–1255, 2016, doi: 10.1016/j.energy.2016.10.031.

[42] S. H. Han, J. S. Park, K. S. Lee, W. S. Park, and J. H. Yi, "Evaluation of vertical axis turbine characteristics for tidal current power plant based on in situ experiment," *Ocean Eng.*, vol. 65, pp. 83–89, 2013, doi: 10.1016/j.oceaneng.2013.03.005.

[43] M. A. Singh, A. Biswas, and R. D. Misra, "Investigation of self-starting and high rotor solidity on the performance of a three S1210 blade H-type Darrieus rotor," *Renew. Energy*, vol. 76, pp. 381–387, 2015, doi: 10.1016/j.renene.2014.11.027.

[44] P. M. Kumar, K. R. Ajit, M. R. Surya, N. Srikanth, and T. C. Lim, "On the self starting of Darrieus turbine :An Experimental investigation with secondary rotor," *2017 Asian Conf. Energy, Power Transp. Electrif. ACEPT 2017*, vol. 2017-Decem, pp. 1–7, 2017, doi: 10.1109/ACEPT.2017.8168545.

[45] V. Patel, T. I. Eldho, and S. V. Prabhu, *Experimental investigations on Darrieus straight blade turbine for tidal current application and parametric optimization for hydro farm arrangement*, vol. 17. Elsevier Ltd, 2017.

[46] G. Saini and R. P. Saini, "Numerical Investigation of the Effect of Blade Profile of a Darrieus Hydrokinetic Turbine," *2018 5th IEEE Uttar Pradesh Sect. Int. Conf. Electr. Electron. Comput. Eng. UPCON 2018*, no. January 2019, 2018, doi: 10.1109/UPCON.2018.8597073.

[47] V. Patel, T. I. Eldho, and S. V. Prabhu, "Performance enhancement of a Darrieus hydrokinetic turbine with the blocking of a specific flow region for optimum use of hydropower," *Renew. Energy*, vol. 135, pp. 1144–1156,

2019, doi: 10.1016/j.renene.2018.12.074.

[48] A. E. Benchikh Le Hocine, R. W. Jay Lacey, and S. Poncet, “Multiphase modeling of the free surface flow through a Darrieus horizontal axis shallow-water turbine,” *Renew. Energy*, vol. 143, pp. 1890–1901, 2019, doi: 10.1016/j.renene.2019.06.010.

[49] A. E. Benchikh Le Hocine, S. Poncet, and J. Lacey, “Numerical Modeling of a Darrieus Horizontal Axis Shallow-Water Turbine,” *J. Energy Eng.*, vol. 146, no. 5, p. 04020050, 2020, doi: 10.1061/(asce)ey.1943-7897.0000700.