26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1433 VARIABLE GEOMETRY DIFFUSER FOR TURBINES IN CAPTURE AND PRODUCTION OF SUSTAINABLE ENERGY: A SYSTEMATIC REVIEW

Elaine Maria Coim, 190137479@aluno.unb.br
Antonio C P. Brasil Júnior, brasiljr@unb.br
University of Brasilia, Campus Darcy Ribeiro, Brasília-DF, 70910-900

Abstract. *Increasingly promising, the concept of sustainability has attracted the interest of researchers in the development of new devices for the capture and conversion of energy. In this context, improvement projects have been developed to maximize power generation. Among them, the horizontal axis turbines shrouded by diffuser present more efficient results in capturing the energy fluid in motion because it increase the mass flow through the turbine rotor. Thus, parameters such as diffuser position about the rotor, angle and expansion length of the tube, and geometric characteristics are studied. More recent research introduces the concepts of adaptive geometry to the device and brings surprising results. This article aims to present a systematic analysis in the literature of variable geometry diffusers used in the capture and production of sustainable energy. An electronic search in the Scopus and Web Science databases was carried out to identify the works already published and to know the results obtained.*

Keywords: A systematic review, Horizontal axis turbines, Variable geometry, Diffuser, Sustainable energy.)

1. INTRODUCTION

The concept of horizontal axis turbine (HAT) in the capture and production of sustainable energy has been several studies in recent decades. A HAT consists of a set of blades with an axis of rotation parallel to the ground that, perpendicularly, faces the flow of fluid to promote work and turning (Johari *et al.*, 2018). In a scenario where the global energy matrix is changing due to the rapid growth in the participation of renewable energy sources, improvement projects are being developed at HAT's to maximize energy generation. In this sense, for many years, the main experiments in horizontal axis turbines addressed geometric characteristics and the number of blades as being the only viable ways to increase their power. However, more recent projects show that a horizontal axis turbine shrouded by diffuser has better results.

First proposed by (Lilley and Rainbird, 1956), experimental studies were conducted by (Oman *et al.*, 1975), (Igra, 1981), (Foreman *et al.*, 1978), (Phillips *et al.*, 2002). His experiments have proven that a horizontal axis turbine shrouded by diffuser (DAT) can extract much more energy from a moving fluid than a conventional turbine of the exact dimensions. After that, other experimental, analytical and numerical studies have been developed to prove the method's efficacy.

Furthermore, recent research developed by (Bagheri-Sadeghi *et al.*, 2018) dynamics simulation (CFD) tool modeled a wind horizontal axis turbine shrouded by diffuser and observed how the geometric characteristics of the diffuser could influence energy conversion. Among others, the angle of attack of the cross-section of the duct was the variable of the design. By adopting the smallest angle, the results proved a better efficiency of the turbine, which may exceed the maximum power coefficient established by (Cp)) Betz's theory. (Ohya and Karasudani, 2010) conducted experimental tests on four different diffusers curvature configurations, one of them presenting (Cp)) of 0.54, manufactured and tested on a wind farm. (Foote and Agarwal, 2013) using the genetic algorithm method, they studied thirteen different optimization cases varying parameters based on actuator disc theory. In this same line, (Amer *et al.*, 2013) developed a study using numerical tools that showed better efficiency in diffusers convexly than conical or concave. Several other studies could be cited. Researchers from the University of Brasília (Nunes *et al.*, 2020) conducted a systematic review on the subject and can be accessed for more detailed studies.

New trends outside the context of sustainable energy capture and generation Quackenbush *et al.* (2005) presented an intelligent duct concept for underwater vehicles. A propellant surrounded by deformable geometry diffuser generated by electrically actuated form memory alloy actuators (SMA). (Muszyński and Strzelczyk, 2013) presented preliminary results of experimental research on variable geometry ducts for propellants. Applying the concept in marine blades (Kapuria and Das, 2018) presented for the first time that it is possible to generate enough torsion to cause the desired improvement in hydrodynamic performance on large-scale surfaces in non-design conditions using (SMA) composite actuator elements.

Nevertheless, little is known how the technique can be applied to diffusers in the sector of turbine shrouded for capture and production of energy. However, the technology can be better disseminated with more cohesive guidelines to facilitate the localization of what has already been tested and which research paths can be adopted. This article aims to comply with this objective by using a systematic methodology of literary analysis to present the most relevant parameters identified in the technique and discuss the initiatives and experiments published about diffusers of variable geometry in the capture and production of sustainable energy.

2. RESEARCH DEVELOPMENT

According to the proposed objective, to achieve as many published studies in the area as possible and identify the most relevant studies, a detailed search for the Scopus and Web of Science databases was carried out. Both databases were selected in the Capes Journals portal for the availability of relevant content for engineering. In addition, they have an excellent advanced search engine capable of reaching a variety of international editors in the scientific and technical fields. Thus, using both tools, achieve with greater precision the most relevant works.

To achieve as many experiments as possible in the literature, the research question was formulated to contain the focused object, the applied intervention, and the type of expected result. Thus, the topic "Variable geometry for turbine diffusers using intelligent materials" was obtained to make the research as objective as possible.

Defined the research topic, the words of greater logical meaning were combined to meet the proposed objective, including their synonyms. Thus, it was possible to identify as many articles published on the subject as possible. The table 1 summarizes the keywords used, associated with Boolean advanced search operators.

Table 1. Database search keywords

Combined keywords	Papers
TITLE-ABS-KEY ((variable* OR adaptive* OR controllable* OR smart* OR responsive* OR fold* OR piezoelectric*) AND (geometry* OR structure* OR shape* OR surface* OR materials* OR line*) AND (diffuser* OR duct* OR shroud* OR concentrator*) AND (wind OR tidal OR marine OR current OR hydro) AND turbine* AND NOT "gas turbine" OR "francis turbine" OR "darrieus turbine" OR pump* OR solar* OR tandem*) AND (LIMIT-TO (LANGUAGE , "English*))	55 Scopus 32 WoS

For the selection of papers, the following criteria were adopted:

- Original articles and review articles;
- Published in English;
- Experimental studies in variable structure duct suitable for horizontal axis turbine in sustainable power generation;
- Observational studies with/without control in the variable structure duct suitable for horizontal axis turbine in sustainable power generation;

Articles that did not meet the established criteria were discarded.

3. REFERENCE PARAMETERS

Once the selection of articles was defined, an extensive effort was used to read and understand the techniques and tools used in developing a variable geometry diffuser for horizontal axis turbines for capture and sustainable energy generation. Therefore, a retrospective of the theory of horizontal axis free turbines and diffusers was necessary.

Conformable (Nunes *et al.*, 2020), the diagram represented by figure 1 illustrates the main parameters used in the horizontal axis turbine system increased by a diffuser that is described in geometric terms: D = diameter, L = total length, Ln = nozzle length, Le = expansion length, h = flange height, and θ = expansion angle.

The equation that describes your area (A) is defined as:

$$A_k = \pi(\frac{D_k}{2})^2, \tag{1}$$

where, $k = i, r, d$, for front diffuser input, turbine rotor, and maximum transverse diffuser session, respectively. The axial velocity of the 'u' flow is the flow speed profile on the turbine axis; parameterized by 'U', the average flow speed.

In general, the energy available in a fluid can be considered kinetic energy and pressure energy. The kinetic energy *(E)* equation, whatever the fluid, is given by the moving mass *(m)* at an average wind speed defined by the following expression:

$$E = (\frac{1}{2})mU^2, \tag{2}$$

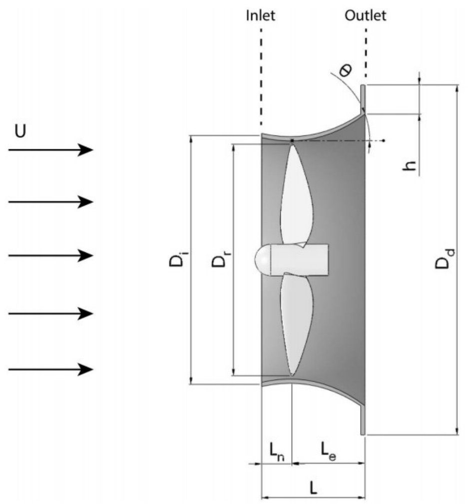

Figure 1. Illustration of parameters on a diffuser shrouded turbine.

Thus, whereas the reduction in pressure is minimal, the density is constant, and the energy of the turbine is given by upstream energy minus downstream energy:

$$E_x = (\frac{1}{2})m(U_\infty^2 - U_w^2), \tag{3}$$

if the fluid does not decrease its speed, then no power has been extracted; if it excessively decreases its speed, then the mass flow will tend to zero, and there will be no rotation; then the intermediate value between U_∞ and for maximum power extraction is U_w known as:

$$U_d = (\frac{U_\infty + U_w}{2}) \tag{4}$$

By definition, power is the rate of variation of the amount of energy supplied or provided by a *(P)* system over a time interval. Thus, you can obtain the equation for the total energy available in the fluid by the equation:

$$P = \frac{dE}{dT} = \frac{1}{2}\dot{m}U^2 = \frac{1}{2}\rho A U^3, \tag{5}$$

considering that the mass flow rate of a fluid with a density $textsl\rho$, through a section *(A)* and velocity *(U)* can be expressed as follows:

$$\dot{m} = \frac{dm}{dt} = \rho A U \tag{6}$$

Once the power available in the fluid is identified by equation 4, the parameter to evaluate the efficiency of the turbine that extracts this kinetic energy is the power coefficient (C_p), defined as the ratio between the useful energy provided by the machine and the energy made available by the flow:

$$C_p = \frac{T \cdot U_d}{(\rho A U_\infty^3)/2}, \tag{7}$$

where *(T)* is the thrust force applied in the direction perpendicular to the plane of rotation of the turbine, given by the expression:

$$T = \dot{m}(U_w - U_\infty) \tag{8}$$

The interest now is to understand the maximum conversion efficiency of the turbine since it cannot convert 100% of the power available in the fluid into energy. This maximum efficiency is known as the 'Betz Limit' and was defined from the assumption that the average gives the fluid speed in the rotor between the upstream speed and the downstream speed. The efficiency of any process is defined as the useful power divided by the available power. Once the necessary mathematical operations are performed, the maximum critical point found is tested. In this sense, when subjected to this maximum point, the turbine power coefficient identifies the maximum possible energy extraction value equal to 59.3.

In addition to these, one can study turbine performance as a function of blade rotation and undisturbed fluid velocity *(TSR)*, represented by the equation:

$$TSR = \frac{\omega R}{U}, \tag{9}$$

where ω is the angular velocity of the rotor and R is the radius of the rotor.

Briefly, the power coefficient and the tip speed ratio are the main parameters to evaluate the performance of a horizontal axis turbine. In dimensionless terms, the Reynolds number can also be considered essential to complete the geometric description of the device. In possession of this knowledge, reading the selected articles brought a better understanding of the techniques used in the research. It could contribute to the evaluation of the most relevant ones.

4. RESULTS

Few papers have stood out within the emerging concept of intelligent diffusers in sustainable energy production and generation. The first of them proposed a diffuser concept with a self-adaptive flange. The project was inspired by Ohya and Karasudani (2010) research, which developed a 3 kW wind turbine with a large flange-mounted on the diffuser outlet, shown in figure 2. When performing wind tunnel tests, they found that the wind flow through the rotor through the diffuser could be increased due to the emergence of a low-pressure region caused by the formation of vortices behind the flange. Numerically proven, the device increased the wind speed at the diffuser inlet by up to 1.7 times, compared to the same conditions as a diffuser without the flange.

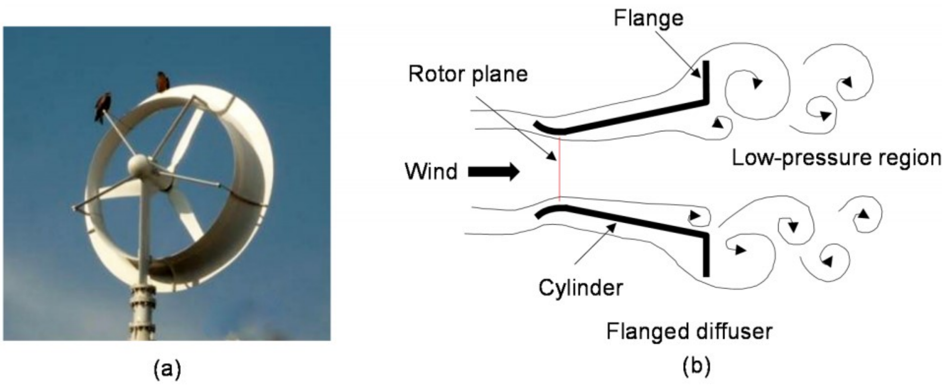

Figure 2. (a) Diffuser concept with flange and (b) Squematic diagram

Shortly before, (Takada, 2009) had already carried out wind tunnel experiments on a 500 W wind turbine shrouded by diffuser. Computational analyses using *CFD* codes showed that the wind load acting on the wind turbine with a compact diffuser was approximately 3.2 times higher than the wind load acting on a turbine without a diffuser but with the same diameter, figure 3 .

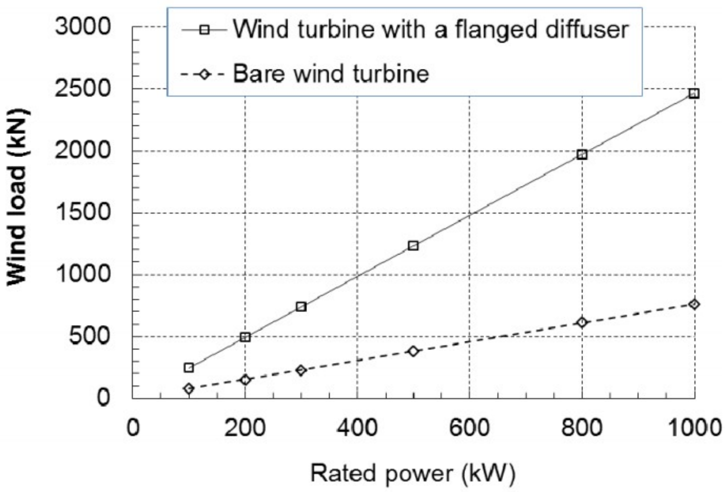

Figure 3. Experimental result using CFD

Given this, (Hu and Wang, 2015) assumed that 69% of the wind load acting on a wind turbine shrouded by a diffuser equipped with a flange is caused by the flange itself. A diffuser equipped with a flange consists of two main parts: the cylindrical part of the diffuser and the flange. Therefore, the wind load will act partially on the cylindrical part of the diffuser and partially on the flange, making it possible to define improvement strategies in both parts independently. Finally, they numerically analyzed an intelligent self-adaptive flange capable of gradually reducing the action of the wind load on the diffuser.

Using two plates in the cantilever system, one end of the flange becomes flexible due to different configurations imposed on the structure material and allows the opening of an escape passage for the higher speed wind, described in figure 4. In other words, the deformation of the back plate is zero or approximately zero for wind speeds below the design speed; reached the maximum design speed, the back plate deforms due to the action of the wind load and reaches the front plate; finally, the wind load acting on the two plates, deform and cause an opening for wind passage, reducing the wind load on the device.

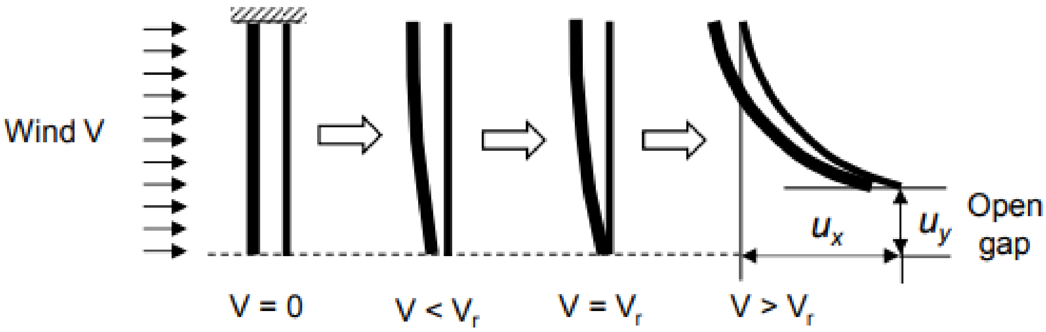

Figure 4. Illustration of the idea of a bi-cantilever flange.

The numerical results proved the effectiveness of the method. A self-adaptive flange can maintain the advantages of a flange-equipped diffuser at low wind speeds and reduce the wind load acting on the diffuser at higher rates. In figure 5, it is possible to visualize the contour of the velocities and the current lines defined by wind acceleration identified around the rigid flange diffuser and the self-adaptive flange diffuser, which in turn has a relatively smaller velocity field because the deformation of the self-adaptive flange allows some of the wind acting on the diffuser surface to flow through the open gap. A similar result is observed in the current lines that exhibit smoother behavior at the diffuser entrance, indicated by the arrow.

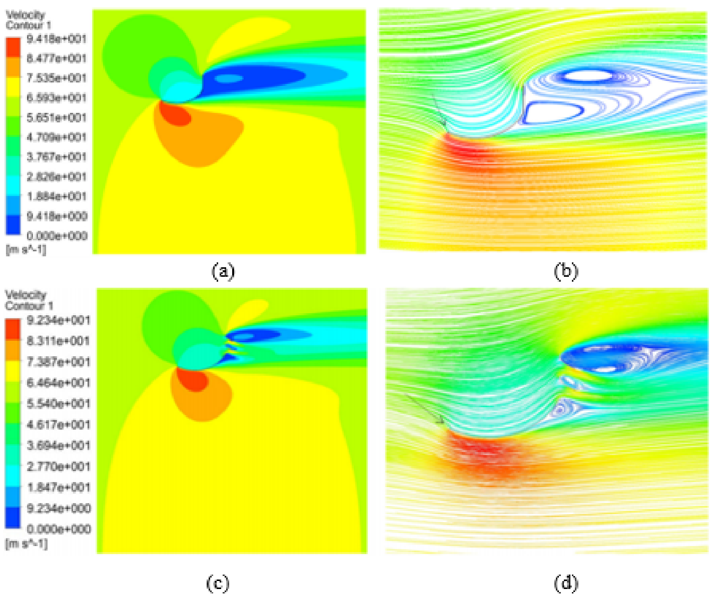

Figure 5. Flow fields around the rigid flanged diffuser and the self-adaptive flange diffuser at 60 *m/s*: (a) velocity countour rigid flange, (b) streamline rigid flange, (c) velocity countour self-adaptive flange and (d) streamline self-adaptive flange

Similarly, researchers at Tarbiat Modares University (Siavash *et al.*, 2020) experimented with a diffuser with a controllable duct to manage turbine performance under different flow conditions. The goal was to design, fabricate, and evaluate a multi-purpose horizontal-axis wind turbine equipped with a controllable diffuser *(TMWT)*. The geometry of the controllable duct consists of two main parts. The first part is a fixed ring located directly around the blades, and the second part is a curved diffuser divided into two parts, one of which is fixed and the other can rotate and partially open the duct.

The wind tunnel tests tried six different configurations: duct-free turbine, fixed ring duct, 180 degrees closed curved duct, 240 degrees closed curved duct, 300 degrees closed curved duct, and 360 degrees closed curved duct, as illustrated in figure 6. Considering the effects of power increase and rotor acceleration proportional to free rotor conditions - PAP (Power Augmented Percent) is represented by the figure 7. As can be seen, the power production is maximum for the main diffuser configuration until it can be resumed to higher levels when operated in the semi-open diffuser configuration under broader TSR conditions.

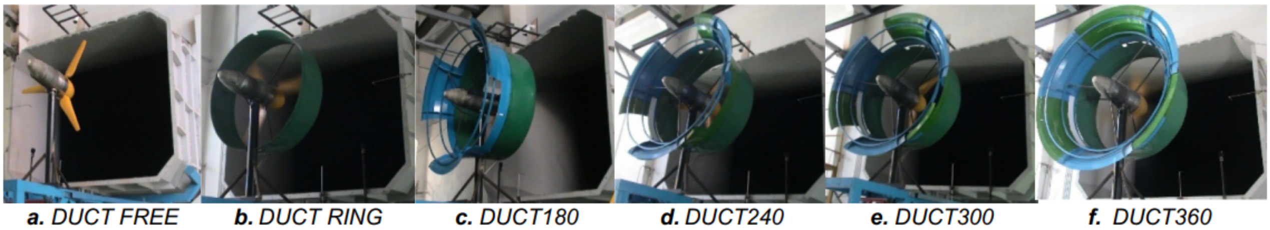

Figure 6. TMWT treatments in wind tunnel test section.

The results showed that a completely closed diffuser could considerably increase the turbine's power in circumstances where the wind speed regime is between 7 to 10 m/s. The same may happen with a simple ring-shaped diffuser. Surprisingly, in conditions where the wind speed can exceed this mark, the semi-open diffuser proved to be more effective and showed a significant increase in power. In figure 8 , you can view the maximum values for Cp and TSR for the experienced wind speeds.

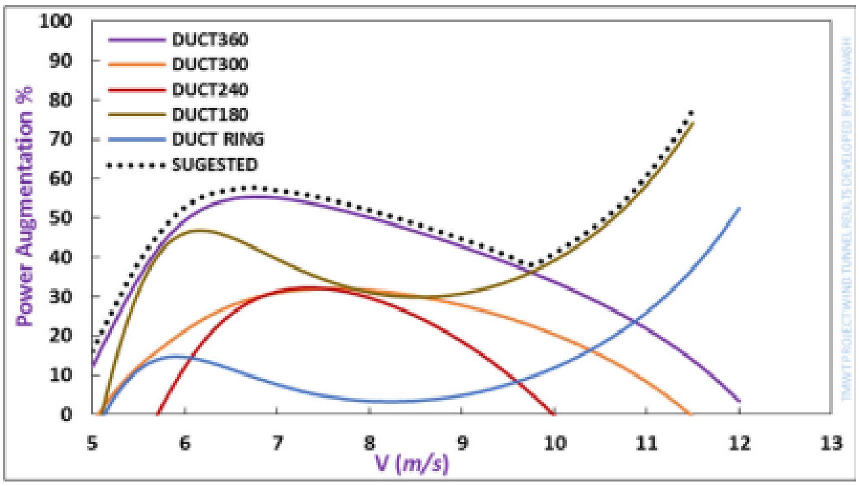

Figure 7. Power augmentation percent proportion to duct free TMWT.

From this perspective, (Watson *et al.*, 2019) presented a paper containing a specialized view of Europe on future emerging technologies in the wind energy sector, among them, intelligent rotors. (Bilgen, 2017) demonstrated the feasibility of an excellent state rotor composed of smart materials for various purposes, such as flow control. (Calabrese *et al.*, 2020) have developed an innovative variable structure control scheme capable of regulating the axis speed of a horizontal axis wind turbine according to wind speed.

5. CONCLUSION

This work was motivated by the emerging concept of intelligent surfaces applicable to power capture and generation devices. The rapid depletion of conventional energy sources and the growing demand for sustainable energy are notorious. For this reason, scholars have been encouraged to do intensive research into more advanced technologies to increase the efficiency of these devices. Thus, a collection of 78 articles resulting from systematic literature research was analyzed. The articles of most significant relevance to the research question defined in this study were selected, and the most important results were presented and discussed.

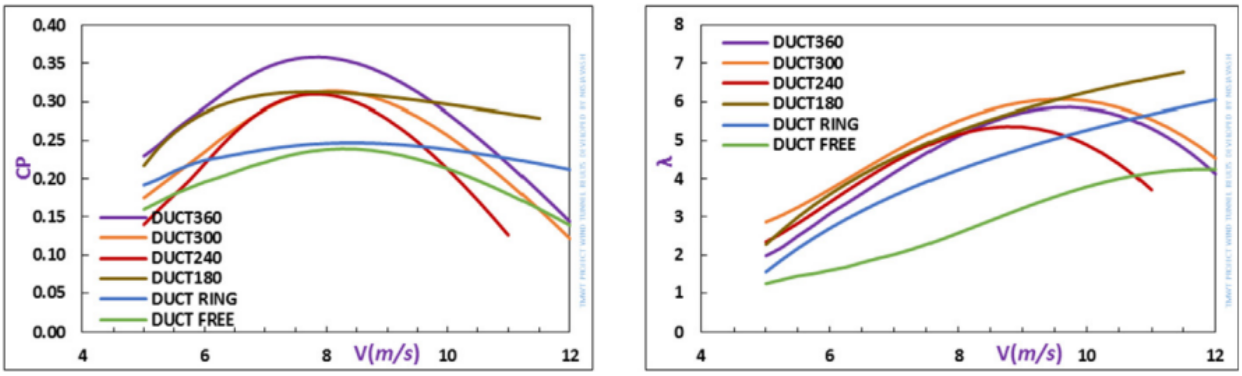

Figure 8. Power coefficient and blade tip-speed ratio for all treatments in experimented wind velocity domain.

The proposed variable geometry for horizontal axis turbine diffusers in the capture and generation of energy is emerging. The concept derived from the significant effects on the aerodynamic loads of the flexible blades begins to adapt to the geometric parameters of the diffuser by presenting a substantial increase in turbine power. Using the diffuser, a negative zone produced from behind can vacuum the fluid through the duct and, as a result, increase the flow speed. Thus, it is essential to know the configuration of the diffuser that best responds to the phenomenon.

In this sense, the diffuser with flange and the curved surface diffuser presented reasonable expectations for implementing the variable geometry concept. A self-adaptive flange is proposed for a wind turbine shrouded by a diffuser to reduce wind loads by acting on the diffuser at high wind speeds. A result that contributes to the maintainability of the device, reducing the effects of excessive vibration. On the other hand, a curved diffuser is proposed to open 180° of its surface as a strategy to control the turbine's performance in different airflow conditions. Results demonstrate the efficacy of the method with a low reduction in the power coefficient for higher TSR.

6. REFERENCES

Amer, A., Ali, A.H.H., ElMahgary, Y. and Ookawara, S., 2013. "Effect of diffuser configuration on the flow field pattern inside wind concentrator". In *2013 International Renewable and Sustainable Energy Conference (IRSEC)*. IEEE, pp. 212–217.

Bagheri-Sadeghi, N., Helenbrook, B.T. and Visser, K.D., 2018. "Ducted wind turbine optimization and sensitivity to rotor position". *Wind Energy Science*, Vol. 3, No. 1, pp. 221–229.

Bilgen, O., 2017. "A piezocomposite rotor with contactless power and data transmission". In *Smart Materials, Adaptive Structures and Intelligent Systems*. American Society of Mechanical Engineers, Vol. 58264, p. V002T04A001.

Calabrese, D., Tricarico, G., Brescia, E., Cascella, G.L., Monopoli, V.G. and Cupertino, F., 2020. "Variable structure control of a small ducted wind turbine in the whole wind speed range using a luenberger observer". *Energies*, Vol. 13, No. 18, p. 4647.

Foote, T. and Agarwal, R., 2013. "Optimization of power generation from shrouded wind turbines". *International Journal of Energy and Environment (Print)*, Vol. 4.

Foreman, K., Gilbert, B. and Oman, R., 1978. "Diffuser augmentation of wind turbines". *Solar Energy*, Vol. 20, No. 4, pp. 305–311.

Hu, J.F. and Wang, W.X., 2015. "Upgrading a shrouded wind turbine with a self-adaptive flanged diffuser". *Energies*, Vol. 8, No. 6, pp. 5319–5337.

Igra, O., 1981. "Research and development for shrouded wind turbines". *Energy Conversion and Management*, Vol. 21, No. 1, pp. 13–48.

Johari, M., Jalil, M. and Shariff, M.F.M., 2018. "Comparison of horizontal axis wind turbine (hawt) and vertical axis wind turbine (vawt)". *International Journal of Engineering and Technology*, Vol. 7, No. 4.13, pp. 74–80.

Kapuria, S. and Das, H., 2018. "Improving hydrodynamic efficiency of composite marine propellers in off-design conditions using shape memory alloy composite actuators". *Ocean Engineering*, Vol. 168, pp. 185–203.

Lilley, G. and Rainbird, W., 1956. "A preliminary report on the design and performance of ducted windmills".

Muszyński, T. and Strzelczyk, P., 2013. "Experimental investigation of a variable geometry ducted propeller". *Advances in Science and Technology. Research Journal*, Vol. 7, No. 17.

Nunes, M.M., Junior, A.C.B. and Oliveira, T.F., 2020. "Systematic review of diffuser-augmented horizontal-axis turbines". *Renewable and Sustainable Energy Reviews*, Vol. 133, p. 110075.

Ohya, Y. and Karasudani, T., 2010. "A shrouded wind turbine generating high output power with wind-lens technology". *Energies*, Vol. 3, No. 4, pp. 634–649.

Oman, R., Foreman, K. and Gilbert, B., 1975. "A progress report on the diffuser augmented wind turbine". In *Proc. 3rd biennal conference and workshop on wind energy conversion systems, Washington, DC, USA*. pp. 819–826.

Phillips, D., Richards, P. and Flay, R., 2002. "Cfd modelling and the development of the diffuser augmented wind turbine". *Wind and Structures*, Vol. 5, No. 2_3_4, pp. 267–276.

Quackenbush, T., Carpenter, B. and Gowing, S., 2005. "Design and testing of a variable geometry ducted propulsor using shape memory alloy actuation". In *43rd AIAA Aerospace Sciences Meeting and Exhibit*. pp. 104105–134117.

Siavash, N.K., Najafi, G., Hashjin, T.T., Ghobadian, B. and Mahmoodi, E., 2020. "An innovative variable shroud for micro wind turbines". *Renewable Energy*, Vol. 145, pp. 1061–1072.

Takada, Y., 2009. "Application of wind lens to the large-scale windmill". *Master Master's thesis, Department of Aeronautics and Astronautics, Engineering School, Kyushu University*.

Watson, S., Moro, A., Reis, V., Baniotopoulos, C., Barth, S., Bartoli, G., Bauer, F., Boelman, E., Bosse, D., Cherubini, A. *et al.*, 2019. "Future emerging technologies in the wind power sector: A european perspective". *Renewable and Sustainable Energy Reviews*, Vol. 113, p. 109270.