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Analyzing and Validating Energy Performance through Computational Simulation of a Helical Vertical Axis Wind Turbine

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ABSTRACT

The planning and analysis of a computational study of a wind turbine are conducted starting from the geometric and physical conditions of a system provided by the manufacturer, up to its simulation using fluid dynamics software. This approach allows for comparing the performance curves of the turbine and developing a planning model to simulate the behavior of new wind systems before their manufacture. The study is based on the fact that many of these designs are currently available commercially through various manufacturers, who sometimes do not provide performance specifications for these devices. Therefore, it is a necessary objective in the field of design engineering to use computational tools that allow the development of the geometry of a helical vertical-axis wind turbine, as well as the simulation and analysis of fluid dynamics and energy performance results, thus validating the systems before their purchase and implementation. The study provided velocity field profiles throughout the turbine for operating ranges from 0 to 12 m/s, as well as the ideal and operational power coefficient of the simulated turbine, along with the energy potential it can generate. It is worth mentioning that the ideal performance obtained through the simulated model corresponds to an additional 20% of the performance presented by the manufacturer's data, highlighting an 80% conversion efficiency from mechanical to electrical power. The study concludes that the values obtained by simulating the turbine and comparing them with the manufacturer's parameters align satisfactorily, dispelling doubts about the energy performance of the studied turbine.

1. Introduction

Currently, there is an incentive to explore methods that allow for sizing and evaluating energy capture in an alternative way to better conserve and ration natural resources. Additionally, the United Nations in its Sustainable Development Goals (SDGs) promotes the use of sustainable energy sources such as wind energy, with this being one of the ways to make reasonable use of energy.

Focusing on studies related to energy generation through wind turbines and the use of computational fluid dynamics (CFD) tools, Chan *et al.,* [1] investigated the blade shape of a Savonius-

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type wind turbine to enhance its power coefficient using computational tools. They evaluated its performance by optimizing the design, achieving improvements of up to 33% in turbine performance. Furthermore, Zemamou *et al.,* [2] conducted a review of works related to the use of Savonius-type vertical axis rotors as an alternative energy generation source, emphasizing the performance of these rotors.

In studies conducted by Peiravi and Ganji [3] investigated the use of vertical-axis helical wind turbines to propose new methods for capturing energy to supply power to street lighting systems. The study demonstrates the energy potential of these wind turbines for each proposal, highlighting their significant contribution to the optimization of these energy systems. Additionally, Peiravi and Ashabi [4] modeled the physical behavior of these systems through the analysis of physical stress, displacements, deformations, and combined von mises stresses, demonstrating the importance of conducting a comprehensive structural analysis before manufacturing the vertical-axis helical wind turbines.

On the other hand, Khanjanpour and Javadi [5] conducted an experimental design with a mixed-level Taguchi approach and CFD simulations to optimize the performance of a hydrodynamic vertical axis turbine. The simulation methods used to model wind rotors depend on the turbulence models implemented, mesh refinement techniques, and domain segmentation as a mesh motion strategy to prevent dislocations in the elements comprising the grid, as done in previous studies [6-9].

Therefore, in addition to CFD simulation techniques and mesh generation criteria, the type of rotor implemented must conform to mesh motion controls. Among these types, we have vertical axis turbines such as Darrieus, Savonius, H-type, and other variants with helical blades in the design. These types of vertical axis rotors often have low power coefficients (*Cp*) compared to horizontal axis rotors, prompting various studies to propose modifications to increase their performance [10-13]. Horizontal axis wind rotors are known for their NACA airfoil-shaped blade profile, which enables good aerodynamic adaptation to the drag and lift forces exerted by the wind. They generally have a relatively high Cp, depending on the number of blades integrated into the turbine, as shown in the investigations [14-20].

Other finite element techniques linked to CFD contribute important strategies, such as selecting appropriate turbulence models for the system under study and designing boundary conditions for proper volumetric mesh generation. This ensures that the solver converges more easily during iterations.

Furthermore, the specific characteristics of the phenomenon being studied guide the direction of the simulation. These characteristics may encompass environmental factors, fluid properties, thermal behavior of materials, and other aspects indicated in previous studies [21-27].

Considering the aforementioned points, the objective of this research is focused on the path to simulate, through CFD, the dimensioning, behavior, and validation of the design of a helical-bladed vertical axis turbine. This study aims to evaluate and analyze its performance as a wind generator compared to an experimental model.

2. Materials and Methods

To assess the energy and fluid dynamic behavior of a vertical axis turbine model, it becomes necessary to be acquainted with the types of turbines that can be designed and are commercially available. This knowledge allows for an assessment based on manufacturer data sheets. The theoretical models applicable to these designs enable the determination of the potentials these turbines can support.

However, once the turbine model to be evaluated is chosen, it becomes necessary to represent it in CAD and CFD software to simulate its behavior under input variables such as wind speed. Assigning turbulence models, boundary conditions for the design to be simulated, and solver programming contribute to a proper estimation of the energy performance of the simulated turbine, allowing validation with the experimental model provided by a manufacturer. Refer to Figure 1 for the process flowchart.

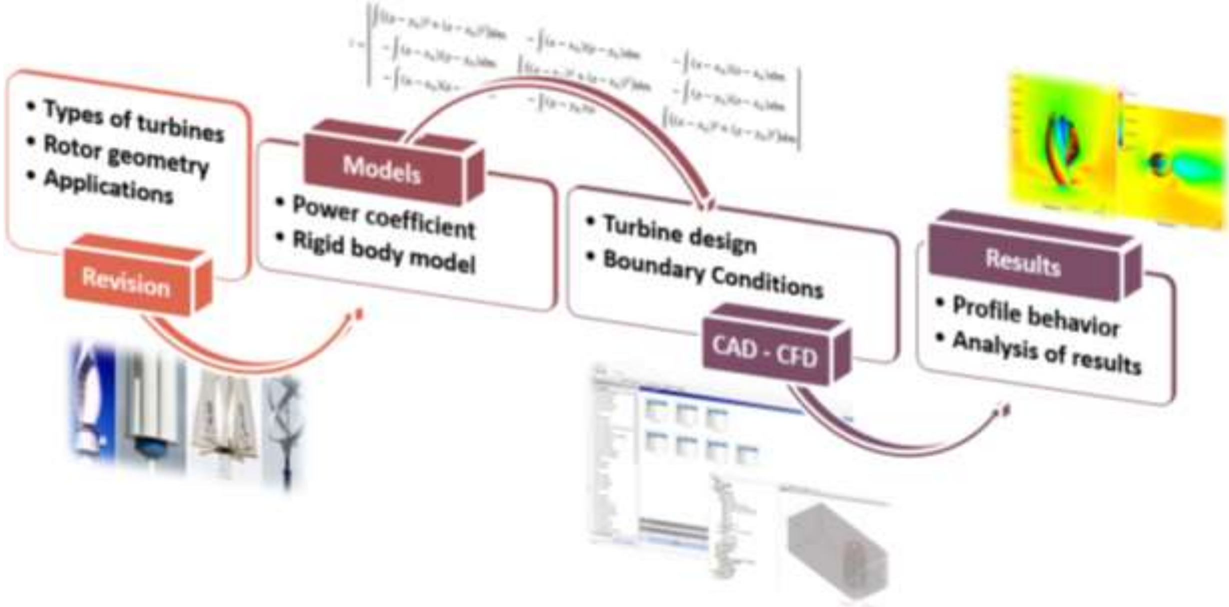


Fig. 1. Process flowchart for simulating a wind turbine

With the methodological route established for simulations using CFD tools, allowing the characterization of a helical-bladed vertical axis turbine used for low-power energy supply, and with the performance coefficient validated by comparing a real system with the simulated one, the design characteristics of the real model must be obtained. See Table 1 for properties below.

Table 1
Physical properties of the systems

Properties Wind Turbine	
Generated Power (W)	200
Blade Diameter (m)	0.42
System Weight (kg)	20
Blade Height (m)	0.9
Number of blades	2
Swept area (m^2)	0.378

Once the physical characteristics of the system are identified, the CAD model of the turbine is generated using CAD software. Applying appropriate materials and dimensions allows for the calculation of the fundamental moments of inertia governing the system. Refer to Figure 2 for details.

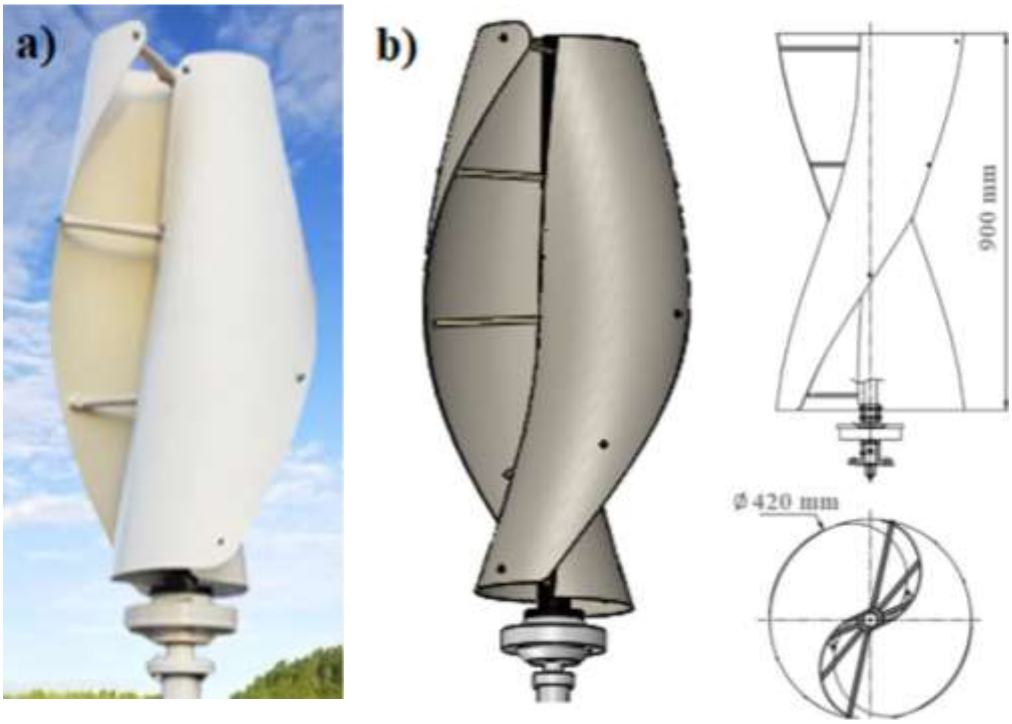


Fig. 2. (a) Physical system, (b) CAD design of a helical vertical axis turbine

Having designed the CAD system of the turbine to be simulated, the generation of an appropriate volumetric mesh is undertaken to conduct a simulation of a domain with rotational motion. This requires creating a stationary domain and a cylindrical subdomain that allows for a proper boundary interface coupling and facilitates rotational movement. Figure 3 illustrates the volumetric meshing scheme of the turbine's boundaries and a cross-sectional view for the coupling of the stationary and mobile interfaces.

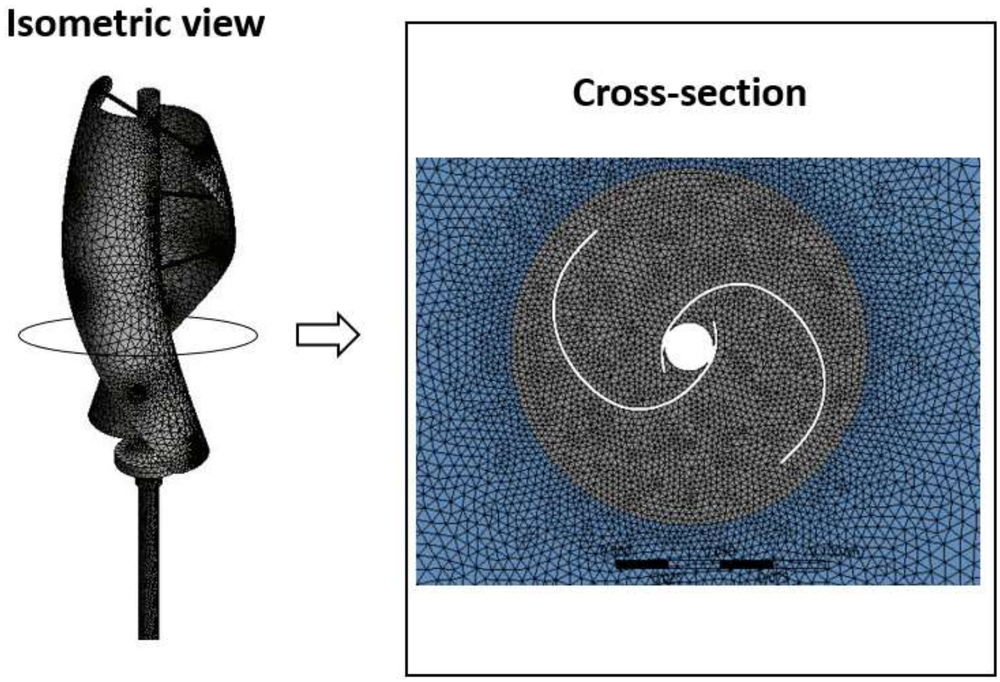


Fig. 3. Volumetric meshing of the system and cross-sectional view

With the CAD and mesh generation established, to ensure proper discretization during the post-processing stage, it is necessary to identify theoretical models that support the physical behavior of the system. Beginning with Betz's Law, which is a fundamental principle in aerodynamics and establishes the maximum theoretical efficiency with which a wind turbine rotor can convert the kinetic energy of the wind into mechanical energy, the maximum energy conversion efficiency achievable in a wind turbine is 59.3%. This means that no more than 59.3% of the kinetic energy of the wind passing through the rotor can be converted into mechanical energy.

The Tip Speed Ratio (TSR) is an important parameter in the operation of wind turbines, representing the ratio between the tip speed of the rotor blades and the incident wind speed. The TSR varies depending on the turbine design but typically falls within the range of 0 to 2 for vertical axis Savonius-type turbines and their derivatives, such as helical-type turbines. An appropriate TSR allows for maximum energy extraction from the wind without exceeding the Betz limit. See Eq. (1) for reference in a study by Mosbahi *et al.,* [28].

$$TSR = \frac{V_{Rotor}}{V} = \frac{wR}{V} \tag{1}$$

where V_{Rotor} is the tangential velocity of the turbine rotation, V is the wind speed, w is the angular velocity of the rotor, and R is the radius of the turbine blades.

The power coefficient (Cp) is a measure used to evaluate the efficiency of a wind turbine. It is calculated by dividing the mechanical power output of the turbine by the kinetic power available in the wind passing through the rotor's swept area, as indicated in previous studies [29-32]. A fully idealized Cp would reach a maximum of 59.3% according to Betz's Law, while for vertical axis Savonius-type turbines and their derivatives like helical-type turbines, it varies within the range of 0 to 35%. as shown in Eq. (2) found in a study by Mosbahi *et al.,* [28].

$$C_P = \frac{P_T}{P_A} = \frac{P_T}{\frac{1}{2}\rho S V^3} \tag{2}$$

where P_T is the mechanical power generated by the turbine, P_A is the kinetic potential generated by the wind movement through the rotor's swept area, S is the rotor's swept area, and ρ is the air density.

Next, the *k-ω* turbulence model is selected for numerical simulation of turbulent flows. This model combines two transport equations representing two key turbulent properties, turbulent kinetic energy k and turbulent dissipation rate ω. It is represented by Eq. (3) and Eq. (4) found in a study by Mosbahi *et al.,* [28].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\Gamma_k \frac{\partial k}{\partial x_j}\right] + G_k - Y_k + S_k \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left[\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right] + G_\omega - Y_\omega + S_\omega \tag{4}$$

In these equations, u is the fluid velocity, G_k represents the generation of turbulent kinetic energy due to mean velocity gradients, while G_ω represents the generation of ω. Γ_k and Γ_ω denote the effective diffusivity of k and ω, respectively. Y_k and Y_ω represent the dissipation of k and ω due to turbulence. S_k and S_ω are user-defined source terms.

Having specified the turbulence model, the rigid body motion model is activated to simulate the turbine's rotation while resisting movement. This generates the torque needed to calculate the final power generated by the rotor. The moment of inertia *I*, which depends on the geometric features of the turbine in the *x*, *y*, *z* axes, and its mass *m*, is represented in Figure 4.

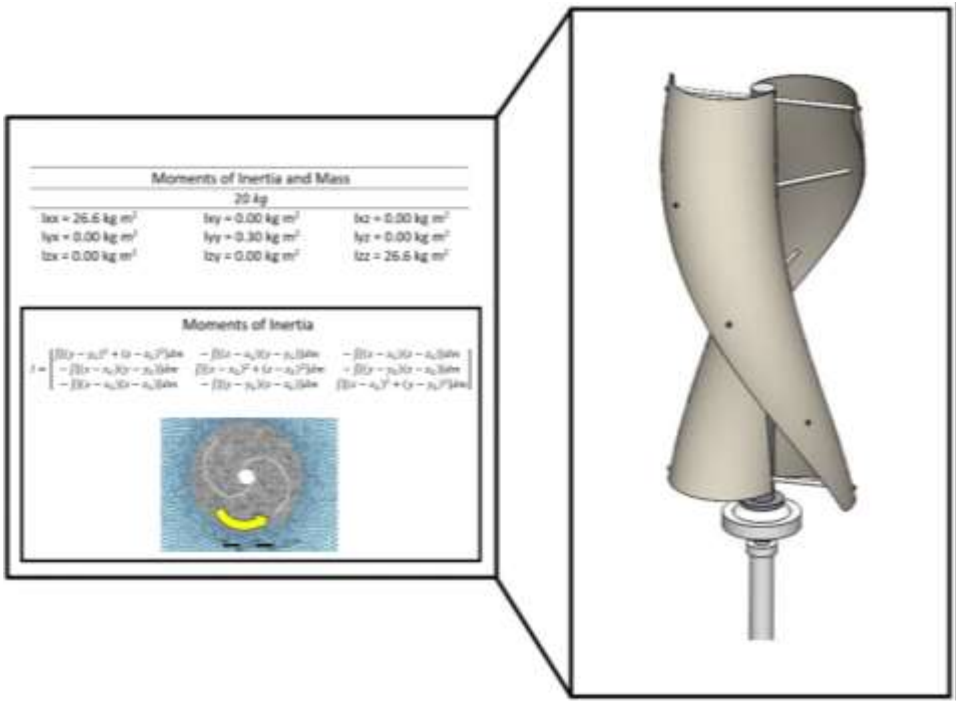


Fig. 4. Inertial characteristics of the studied helical turbine

The assignment of boundary conditions corresponds to the wind velocity inlet, atmospheric pressure outlet, symmetry conditions to avoid simulating the effect of a wall blocking the wind, a subdomain with a rigid body motion condition for rotation, and a stationary main domain, as shown in Figure 5.

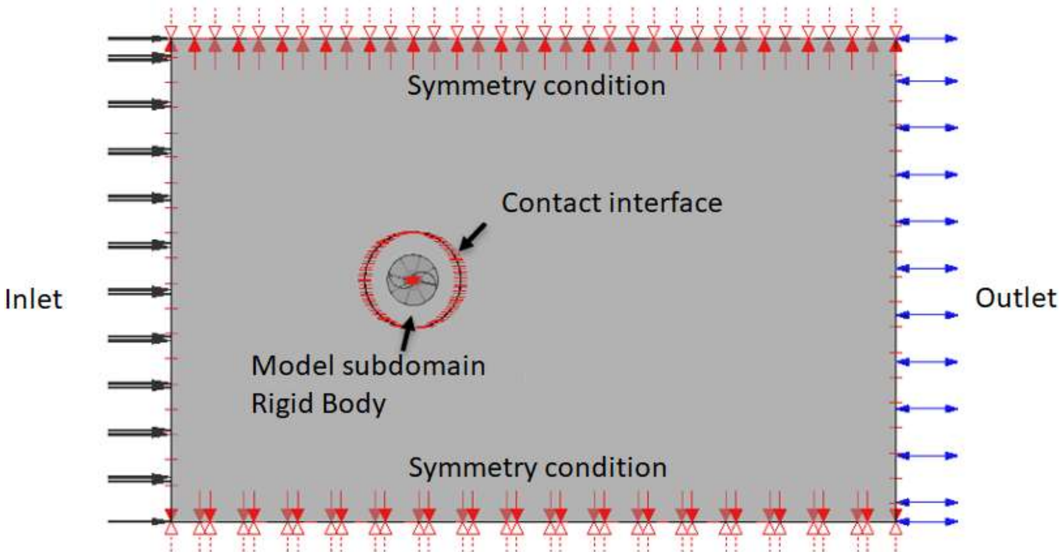
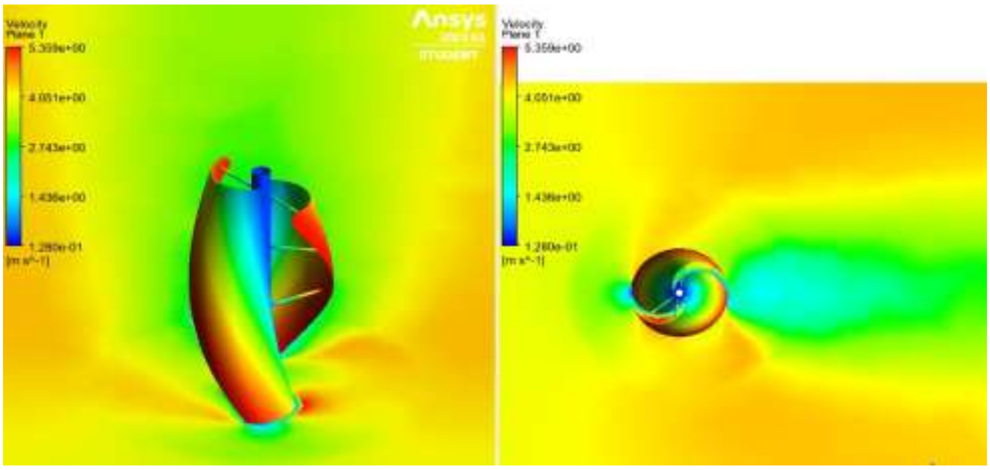


Fig. 5. System boundary conditions

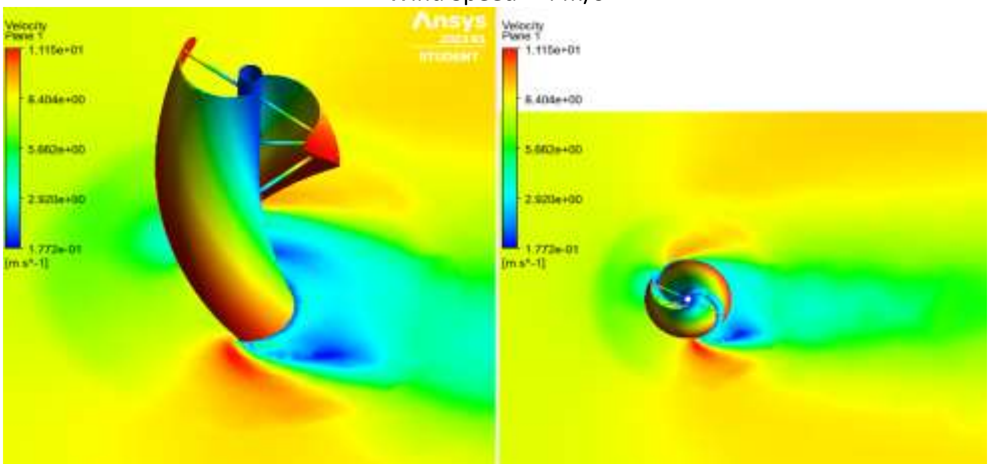
3. Results

Once the system is modeled, velocity profiles and wind wakes describing the fluid dynamic behavior of air passing through the turbine blades are obtained, along with the torque behavior, rotor angular velocity, TSR, and *Cp* of the system. Figure 6 presents velocity contours for the turbine.

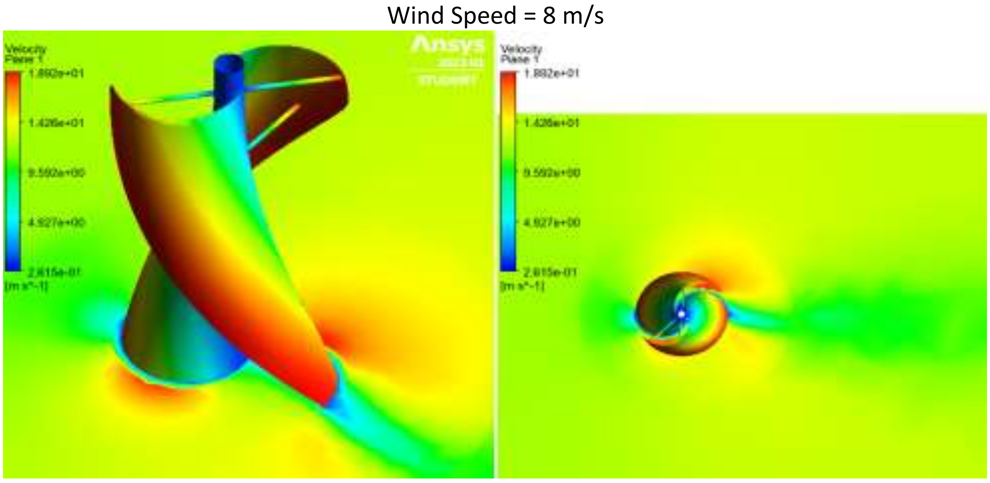
Velocity ranges from 0 to 12 *m/s* were simulated to characterize the turbine with respect to the behavior provided by the design manufacturer for real conditions.



Wind Speed = 4 m/s



Wind Speed = 8 m/s



Wind Speed = 12 m/s

Fig. 6. Velocity profile of the system

From the velocity profiles, areas where the blade tip speed increases when the wind impacts the turbine at a certain speed can be highlighted. This allows us to obtain the theoretical TSR value by dividing the maximum speed reached by the blade tip by the wind speed at that moment. For the established speed range of 0 to 12 *m/s*, TSR values ranged from 1.1 to 1.6.

Furthermore, the total potential energy generated by the turbine for the implemented speed range was quantified, and a comparison was made with the behavior of the actual turbine provided by the manufacturer, as shown in Figure 7.

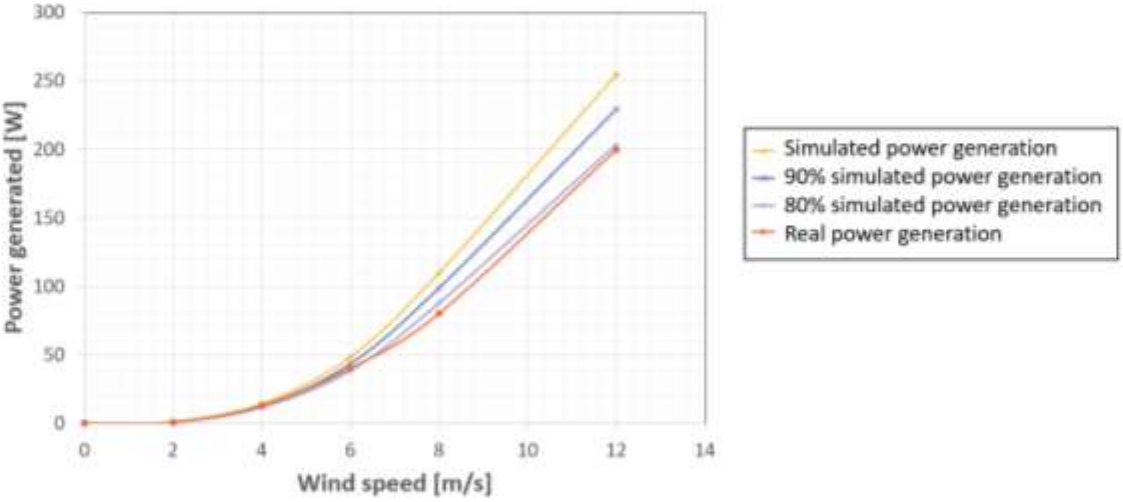


Fig. 7. Potential generated by the simulated helical wind turbine

As observed in Figure 7, the behavior of the power generated provided by the manufacturer closely resembles 80% of the potential generated by the simulated system. This can be explained by indicating that the power generated provided by the manufacturer represents the total electrical conversion, which transformed the mechanical potential of the turbine into electrical energy through an electrical generator with efficiencies ranging from 70% to 80% for these devices.

Once this good approximation of the system is obtained and it is validated that the system's behavior provided by the manufacturer complies with theoretical and simulated conditions of energy generation, the Cp values are presented, assuming ideal, 90%, and 80% conditions. See Figure 8.

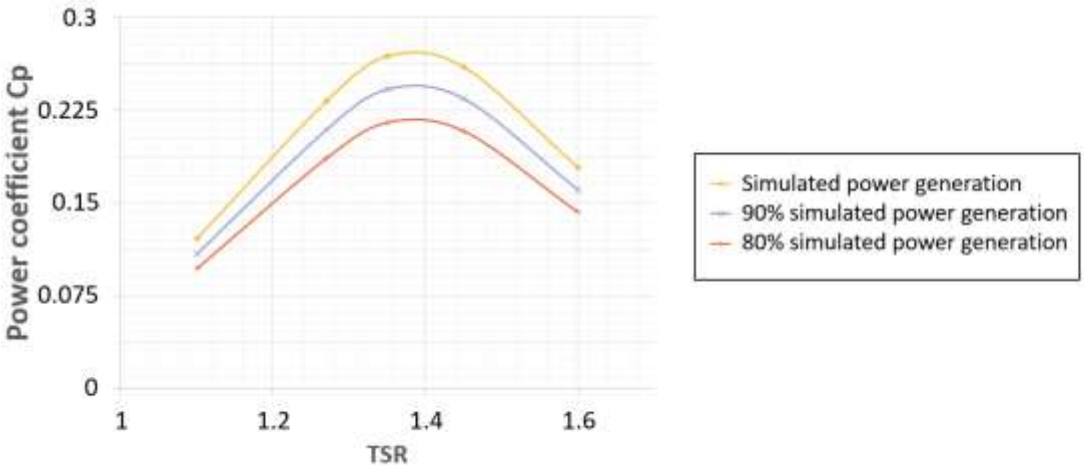


Fig. 8. Power coefficient for the simulated helical turbine

The *Cp* values for the turbine are established within the typical operational ranges for these systems, emphasizing that higher *Cp* values should be achieved by managing TSR values around 1.4.

In an analysis for discussion, it can be observed in the study by Damak *et al.,* [33] that there is a tendency to achieve a Cp around 0.25 for a helical vertical-axis wind turbine, similar to the present study. This contrasts with the study by Jeon *et al.,* [34], which shows a tendency for a higher Cp for the same type of turbines when the swept area is increased.

4. Conclusions

The use of computational tools for the evaluation of wind energy systems offers numerous advantages, including design optimization, conservation of physical resources, and appropriate selection of existing systems.

i. This study analyzes the performance of a vertical-axis turbine using computational modeling techniques to evaluate its fluid dynamic behavior through velocity profiles, generated power, and power coefficient.
ii. The results indicate that the energy performance of the modeled system aligns with the values provided by the manufacturers of the studied helical vertical-axis turbine.
iii. The proposed methodology can serve to validate wind turbines when manufacturers do not provide sufficient data to characterize the expected energy potential under specific environmental conditions.
iv. Finally, the utilization of sustainable energy sources can benefit communities in areas with limited access to electricity services, thereby contributing to the United Nations' Sustainable Development Goals (SDGs).

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