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Study of the efficiency of low-power wind turbines with different roughnesses, by choosing a software for coupling a torque meter and a resistor bench

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ABSTRACT

This research aims to determine if there is a change in the power and torque of a low-power wind turbine when the roughness of its blades is modified by the accumulation of dirt with different grain sizes. The blades' roughness was simulated using sandpaper on the leading edges, using two different screenings and 3 percentages of a chord (15, 25 and 40%). Calculations and previous measurements of the wind turbine in clean condition were made to have a comparative basis, as well as to determine the working Reynolds numbers, concluding that at all times, it worked with a turbulent flow and laminar boundary layer. A torque meter was coupled to the wind turbine to obtain the required measurements of torque and power delivered. The wind turbine was tested in all configurations in a closed wind tunnel with continuous flow. Finally, it was observed that combining the larger grain size of the roughness with the higher percentage of chord results in less power and less torque in the wind turbine; therefore, both conditions decrease the operating parameters of the low-power wind turbine.

Keywords: Wind turbines, efficiency, low power, variable roughness.

RESUMEN

La presente investigación tiene como objetivo determinar si existe un cambio en la potencia y el torque de un aerogenerador de baja potencia, cuando la rugosidad en sus palas se ve modificada por acumulación de suciedad con tamaños de granos diferentes. Se simuló la rugosidad en las palas mediante el uso de lijas en los bordes de ataque, utilizando dos tramados diferentes y 3 porcentajes de cuerda (15, 25 y 40%). Se realizaron cálculos y medidas previas del aerogenerador en condición de limpio para tener una base comparativa, así como también se determinaron los números de Reynolds de trabajo concluyendo que en todo momento se trabajó con un flujo turbulento y capa límite laminar. Se acopló al aerogenerador un torquímetro para obetener las medidas requeridas de torque y potencia entregadas. El aerogenerador se ensayó en todas las

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configuraciones en un túnel de viento cerrado con flujo continuo. Finalmente, se observó que al combinar el mayor tamaño de grano de la rugosidad con el mayor porcentaje de cuerda se obtiene menos potencia y menos torque en el aerogenerador, por lo tanto ambas condiciones hacen disminuir los parámetros de trabajo del aerogenerador de baja potencia.

Palabras clave: Aerogeneradores, eficiciencia, baja potencia, rugosidades variables.

1. Introduction

Windmills have been used for at least 3,000 years for electricity generation, dating back to the end of the 19th century[1]. The world is experiencing an ever-increasing demand for electrical energy, and several alternative energy industries have been developed, such as wind energy, kinetic energy that comes from the movement of a mass of air, i.e., wind. Aerodynamics plays a very important role in the generation of wind energy. In this sense, a wind turbine is an aerodynamic machine that extracts kinetic energy from the wind and transforms it into mechanical energy [2]. The aerodynamics of wind turbines is based on modeling and predicting aerodynamic forces on solid structures and wind turbine blades [3]. In the earth, the movement of air masses is mainly due to the different pressures existing in the different places, moving from high to low pressure. This type of movement is called geostrophic wind. When generating electrical energy from wind, attention must be paid to local winds such as sea breezes or mountain winds. The term wind comes from the Latin "Aeolicus," which refers to Eolos, the god of winds in Greek mythology.

The wind energy industry has made great advances in recent years; the objective of seeking ever cleaner and more economical energy has led to the particular emphasis being placed on characterizing wind turbines and their components to evaluate their optimum performance under different operating conditions, thus making the most of the energy generated by the wind.

The aerodynamics of a wind turbine is highly complicated since problems include understanding and predicting aerodynamic loads of non-stationary blades and rotor performance, prediction of dynamic stresses and the aeroelastic response of the blades, among others. In addition, wind turbines are subjected to complicated environmental effects, such as atmospheric turbulence, ground boundary layer effects, and directional and spatial variations of wind shear [4].

The aerodynamic efficiency of wind turbines and the power with which they work have been two of the aspects that have been explored. The power problem has been well solved for low, medium and high-power wind turbines, while the efficiency of the blades is a subject that is still a source of study for many specialists.

With the increasing use of low-power wind turbines for domestic use and the supply of small batteries in general, there is a need to study the aerodynamics of wind turbine blades under different circumstances in greater depth.

Low-power wind generators deliver up to 100 kW of power, are mainly used to supply homes and small establishments, and are almost exclusively reserved for the private sector.

The evolution of wind turbine power generation costs depends directly on the wind turbine performance, which depends on the characteristics of the turbine blades and their surface roughness [5].

From the point of view of fluid dynamics, roughness can be defined as a surface extension of a body that penetrates the viscous layer of the fluid in contact with the fluid wall, called the boundary layer. These elements increase the surface area of interaction between fluid and solid, causing irregularities and disturbing the flow field within the boundary layer. Consequently, the energy transfer between the surface and the fluid increases, which affects the aerodynamic performance of the airfoils that make up each blade [6].

Mathematical modeling and numerical simulation of the proposed physical models can help understand the phenomenon and conclude whether the predictions are fulfilled. Furthermore, options of using different wake models can be considered to see how it affects the results, using, for example, Windsim simulation codes, which allows the use of nonlinear equations to model the terrain and wind with the obtaining of power curves in order to see the effect it causes [7].

Wind turbines are inevitably exposed to prevailing conditions on site that may contain particles, and even insects, which erode or contaminate the blade surfaces. Among these contaminants, dust, ice and insects are the agents that most increase blade roughness [8]. In addition, the surface roughness of wind turbine blades deteriorates due to various environmental conditions, such as ice or sand [9]. Therefore, the wind turbine with the maximum efficiency is defined as an ideal wind turbine with three main characteristics: the lift-to-drag ratio is infinite, and it has a sufficient number of blades so that the tip and root losses of the blades can be ignored. Therefore, the most important performances of a horizontal-axis wind turbine are power, torque, lift and thrust [10].

The following is a description of the existing concepts and developments in wind energy summarized in two main topics: Wind energy and wind turbines, and Wind turbine efficiency study.

Wind Energy

Wind energy is the energy obtained from the transformation of the kinetic energy generated by the wind to obtain mechanical energy. This mechanical energy can be used for different purposes, particularly if an electric generator is coupled to it; electrical energy can be generated.

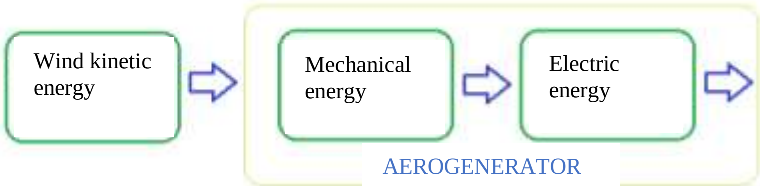

Figure 1. Energy transformation scheme.

The wind turbine is a rotating mechanical device with blades driven by the wind (kinetic energy) that move an electric generator; as the shaft rotates, electricity is generated, which in principle is alternating current and can be transformed into direct current; the faster the blades rotate (higher wind speed), the more electrical energy can be generated [10]. In Figure 2, it can be observed how the air hits the aerodynamic surfaces of the wind turbine.

Figure 2. Wind incidence on the wind turbine.

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<u>Global Wind Potential</u>

Wind energy is one of the oldest forms of energy used by humanity. Since the beginning, people have used windmills to grind grain or pump water. With the advent of electricity at the end of the 19th century, the first wind turbines were based on the shape and operation of windmills. However, until recently, electricity generation by wind turbines has not played a major role.

With the first oil crisis in the 1970s, especially since the anti-nuclear energy movements in Europe in the 1980s, interest in renewable energies was aroused. This led to the search for new ways of exploiting the earth's resources in an ecologically and economically profitable way.

The advantages of the use of this type of energy are its possibility of constant renewal, its abundant presence and its non-polluting effects since its use helps to reduce greenhouse gas emissions considerably, hence its denomination as green energy, as has been proven by Peacock [11] of the School of Engineering and Physical Sciences of the Heriot-Watt University in the United Kingdom, who conducted several studies on low-power wind turbines between 0.4 and 2.5 kW. These have been located in several buildings in the United Kingdom to generate energy that does not emit CO2 and thus help reduce this gas. Moreover, as a result of the analysis of the wind turbines located in the urban perimeter, it was possible to characterize the average wind speeds prevailing in the sector and thus obtain the power curves.

In addition, it also calculated the national average of CO emissions$_{2,}$ obtaining a value of 0.43 kgCO_2 /kWh with a variable rate of 3.5%. With this, it was possible to establish a table of values of the annual production of wind turbines of different powers.

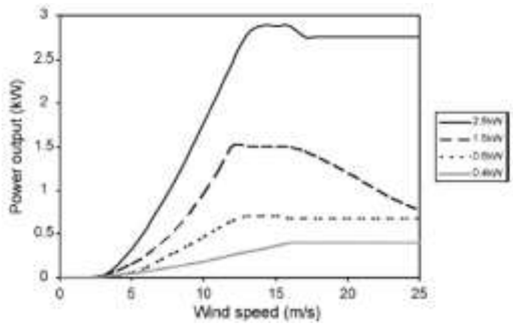

Figure 3. Wind turbine power curves [2].

Predicted annual energy yield of four turbines for two different wind regimes

Turbine rating (kW)	Estimated annual energy yield (kWh)	
	"Low" wind site	"High" wind site
0.4	79	567
0.6	180	1488
1.5	277	2541
2.5	496	4879

Figure 4. Power table [2].

In contrast, the primary defects that could be attributed to it are the intermittency that it sometimes presents, mainly due to the variation of wind intensity during the different times of the year, which can be solved with battery-type energy accumulators, and the noise, which in recent years has been corrected through design.

In recent years, the installed wind power capacity worldwide has been increasing due to the growing demand for electricity and the need to implement healthy energies for the planet. Europe is the excellent wind reference par excellence. It is largely responsible for the growth of installed wind power, so wind power in the world

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grew by 44% in 2014, reaching 369,553 MW, according to data from the Global Wind Energy Council (GWEC). China, the United States, Germany and Spain are the world's leading producers. The following graph shows the evolution of installed wind power from 1998 to the end of 2021 [12].

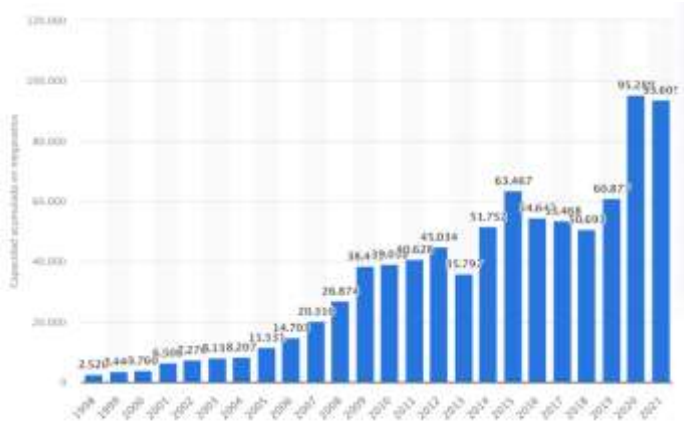

Figure 5. Annual installed wind power capacity in the world 1998-2021.

Each region's capacity to produce wind energy gives the whirlwind potential. This is based on a measurement of the intensity with which the wind circulates, indicating how many W/m^2 can be obtained in each place on the planet. Figure 5 shows a decrease in installed wind power capacity in 2013 and a considerable growth in 2020. Figure 6 shows the distribution of wind potential in the world and finds areas in which winds are very dominant and allow a great potential, as is the case of southern Argentina, in which the potential can reach 7.2 W/m^2.

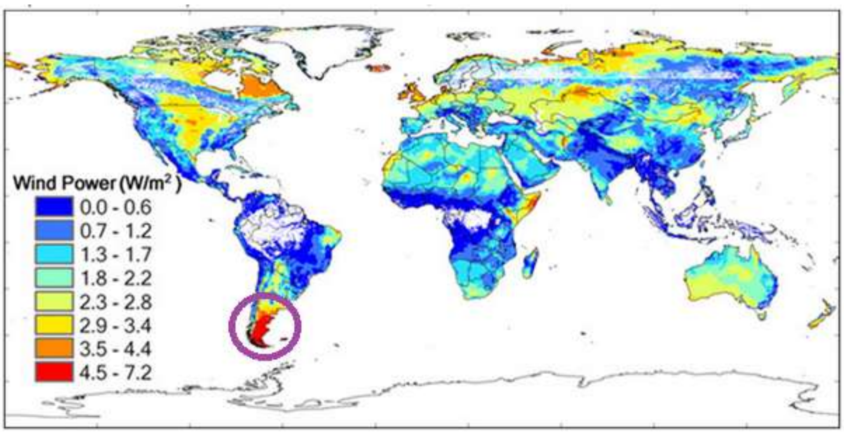

Figure 6. World Wind Potential
Source: Global Wind Energy Council (GWEC)

<u>Wind Power Potential in Argentina</u>

Harnessing the potential of wind has a great advantage over the energies currently used to generate electricity, such as thermal energy. Using wind energy to produce electricity avoids the gas emissions generated by thermal energy and maintains the planet's climatic stability. According to worldwide experience, it is known that with average winds above 5 m/s it is feasible to use wind resources for electricity generation. For example, Argentina has about 70% of its territory winds whose average annual wind speed, measured at 50 meters above ground level, exceeds 6 m/s, as shown in Figure 7.

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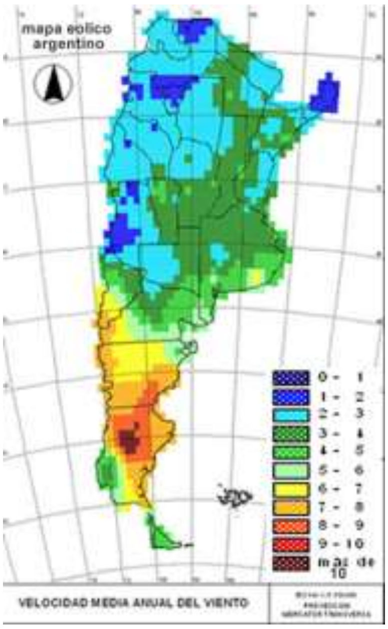

Figure 7. Wind Map of Argentina

The Atlantic coast of the Province of Buenos Aires has winds similar to those of the Baltic and North Sea coasts, over 7 m/s. Many areas in middle and southern Patagonia have average wind speeds exceeding 9 m/s and up to 12 m/s (in general, on-shore wind farms[1] in Europe are located in places with average wind speeds of 7 m/s). There are also other regions in Argentina with average wind intensities between 7 and 10 m/sec, not only on the Atlantic coast of Buenos Aires but also in several central provinces.

This source of electric energy is significant given the amount of energy that can be produced and because of its low production costs today, especially for its generation in the Patagonian region and the southern areas of the Argentinean sea, since this is where there is the greatest potential for converting electric energy through wind generators, and above all, because it is a known technology that has existed for many years and has an energy production cost similar to other energy sources such as fossil fuels or hydroelectric energy [13].

Wind Farms in Argentina

Argentina has only 55 MW installed in wind farms, considering that Argentina's wind potential exceeds 2,000 MW (less than 3%). In Argentina, the average citizen consumes 1200 kWh per year, and considering the number of inhabitants, the daily electricity consumption in Argentina is around 6,000 MWh. Thus, the installed wind power currently represents only 0.92% of the electrical energy needed per hour. If all the country's wind power potential were harnessed, this percentage could be increased to 33.3%. Electric cooperatives between 1994 and 2008 mainly installed the existing wind farms. Although this value has grown in recent years, it is well below the values used in other countries.

Several wind farms are operating in Argentina. Almost all of the wind farms in operation supply a captive local grid of users who are customers of the cooperative, as a local distributor, and feed surpluses into the grid. In

[1] **On-shore:** Onshore. In general, the term wind on-shore is used to refer to wind on land.

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addition, one wind farm (Arauco wind farm) completed its second stage of construction in 2014, which dumps its energy directly into the grid. The wind farms installed in Argentina are as follows:

Table 1. Wind farms in Argentina

Name	**Province**	**Date of Commissioning**	**Potential (KW)**	**Average Annual Speed (m/s)**	**Operator**	**State**
Jorge Romanotti	Chubut	01/05/2005	2.400	8,2	Municipality Pico T	Operative
Antonio Moran	Chubut	01/12/2001	17.060	9,4	PECORSA	Operative
Cutral Co	Neuquén	01/10/1994		7,2	COPELCO Coop. Ltda.	Operative
Rada Tilly	Chubut	01/01/1996	610	10,2	Coop. Eléctrica Rada Tilly	Operative
Punta Alta	Buenos Aires	01/05/1998	22.000	9,6	Punta Alta Electric Coop.	Operative
Tandil	Buenos Aires	01/01/1998	800	7,2	Tandil Electric Coop.	Operative
Headband	Chubut	01/03/2011	6.300	10,2	Hychiko S.A.	Operative
Major Buratovich	Buenos Aires	01/01/1997	1.200	7,4	M. Buratovich Electric Coop.	Operative
Darregueira	Buenos Aires	01/09/1997	750	7,3	Coop. Eléctrica Darregueira	Operative
Rawson I and II	Chubut	01/01/2012	80.000	7,8	EMGASUD and ENARSA	Operative
Claromeco	Buenos Aires	01/01/1999	750	7,3	Claromeco Electric Coop.	Operative
Necochea	Buenos Aires	01/03/2010	300	7,8	Sea Energy S.A.	Operative
El Tordillo	Chubut	01/01/2009	3.000	9,4	ENARSA and Chubut Province Gov.	Operative
General Acha	La Pampa	01/01/2004	1.800	7,2	COSEGA Ltda.	Operative
Parque Arauco S.A.P.P.E.M.	La Rioja	01/10/2011 01/02/2014	50.400	7,5	Gov. La Rioja/ENARSA	Operative
Loma Blanca IV	Chubut	01/08/2013	51.000	8,2	Isolux Corsan S.A.	Operative
Veladero	San Juan	01/01/2008	2.000	7,3	Barrick S.A.	Operative

Low Power Wind Energy

Argentina is a pioneer and most experienced country developing low-power wind energy at the regional level. Low-power wind energy is used for unattended installations up to 3 KW. Domestic production began in the nineties in Córdoba by Giacobone División Energía (an organization currently engaged in the production, installation and maintenance of low-power wind turbines)

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and since 2011 also appeared the equipment of Fiasa S.A. and Tecnotrol SRL. One of the leading players in the low and medium power market is INVAP.

A few years ago, a World Bank program to install a 1,500 WHS "wind house system") in the province of Chubut for isolated settlers began to be developed. The first pilot projects were installed, and later more wind turbines were left in charge of a company for their maintenance; however, no maintenance was performed on the equipment, and several stopped working. Currently, in Cordoba, the aim is to motivate users of the public power grid to provide clean energy through low-power wind turbines in exchange for an economic benefit.

In the leading countries in the generation of renewable energies, the development of low-power wind energy has advanced to the point of allowing distributed energy generation, where residential users become generators that work self-sufficiently and feed their surpluses to the public grid. In the country, this modality has not yet been regulated. However, the enormous wind potential of our cities on the Atlantic coast and the entire Patagonian Region would allow rapid development of this new concept in times of energy crisis.

The future of low-power wind energy goes beyond rural use. In developed countries, companies and governments aim to install small home wind turbines that work with the public power distribution grid. In this way, residential users will also be power generators.

Low-power wind turbines are generally used in stand-alone applications such as: supplying electricity to off-grid houses, mobile homes and even boats. However, since, in general, low-power wind turbines are used under a home concept, they are required to have two main characteristics:

- To be economical: This implies that all the extra elements to be placed in the wind turbine for its operation must be taken into account since, due to the variable characteristics of the wind, it is not possible to use the energy delivered by the device directly.

- Simple construction: It is necessary that low-power wind turbines can be manufactured relatively easily, with materials available on the market and that their parts are easy to replace to reduce maintenance costs in the future.

Figure 8. Low Power Wind Turbine

Wind Turbine Efficiency Study

The efficiency of wind turbines is a subject of study that has been studied in recent years, especially in European and North American countries where high-power wind farms are located. Studies have been carried out on high-power wind turbines, obtaining the result that the wind turbine's power is reduced when different types of dirt accumulate on its blades.

A detailed study of the efficiency of wind turbines would not only reveal the causes of this problem, such as dirt on the blades but would also help to find a possible solution to this problem, which causes high costs when faulty parts have to be replaced.

Forces on the wind turbine

When the wind hits the wind turbine, an aerodynamic force produced by the air is generated on the airfoil of the wind turbine blade in reaction to the force exerted by the blade on the wind turbine. This force can be broken down into a component perpendicular to the free stream called *Lift* and another in the direction of the incident wind called Drag. The components of the aerodynamic force can be dimensioned to obtain the lift and drag coefficients, which allows the characterization of the airfoil, the blade and the wind turbine as a whole. The expressions for the aerodynamic coefficients are as follows [14]:

$$C_l = \frac{L}{\frac{1}{2}\,\rho_\infty\,U_\infty^2\,c}$$

$$C_d = \frac{D}{\frac{1}{2}\,\rho_\infty\,U_\infty^2\,c}$$

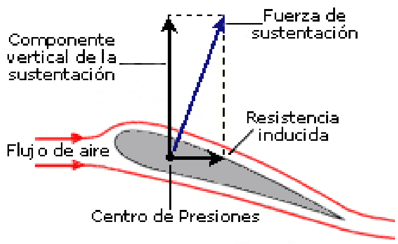

Figure 9. Forces acting on the wind turbine blade.

<u>Reynolds number</u>

The Reynolds number is obtained after dimensioning the momentum conservation equation from the Navier-Stokes equations:

$$Re = \frac{\rho_\infty\,U\,L_c}{\mu_\infty}$$

It is important to remember that low *Re* indicates that the viscosity forces are more important than the inertia forces, presenting a laminar regime in the flow around the profile, while high values of *Re* indicate that the inertia forces have more weight than the forces produced by the viscosity of the fluid.

<u>Loss of Wind Turbine Performance</u>

Wind turbines can be affected in their optimum performance by the presence of foreign particles on the surface of their blades due to their exposure to the elements. In addition, this dirt can significantly affect the power generated by wind turbines; these problems can be caused by:

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- Insect Impact: Due to the high speeds at which wind turbine blades rotate, it is very common for insects to collide with them and get stuck on the surface. The most common fouling pattern is where the dirt accumulates preferentially on the blade's leading edge up to approximately 40-50% of the chord, which can be observed in Figure 11.

Figure 10. Impact of insects on wind turbine blades.

- Ice formation: This happens when the wind farm is located in very cold climates; it is usually the formation of non-uniform layers of ice on the surfaces of the blades, which causes a change in the geometry of the profile, as shown below in Figure 12.

Figure 11. Ice accumulation on wind turbine blades.

- Aging and Sand Storms: Sand storms are frequent in arid climates. The sand particles on the surface generate a change of roughness in the wind turbine blades.

Current studies on the efficiency of wind turbine blades

Studies on the efficiency of wind turbines due to dirt on their blades have been carried out only for high-power wind turbines in countries such as Egypt, the United States and Spain. Among the works carried out on this subject, the following can be highlighted:

Studies with CFD (Computational Fluid Dynamics)

✓ In Chicago, Illinois, Khakpour [15] studied profiles with different roughness to analyze the influence of roughness on the aerodynamic coefficients of the wind turbine blade with S819 profile using sand particles of a specific diameter.

The results showed that the presence of the particles significantly affects the velocity distribution around the profile and with different effects depending on the diameter of the particles, with considerable angles of attack;

however, at zero angles of attack, these effects are not very visible. It was also observed that the angle at which the particles begin to affect the profile's efficiency is when the pressure gradient sign in the intrados and extrados of the profile begins to change, as shown in Figure 12 and 14.

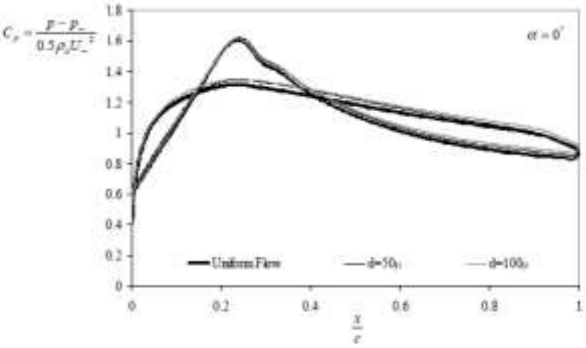

Figure 12. Center of pressures [15].

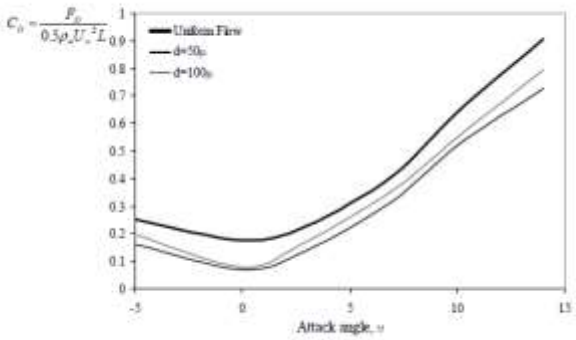

Figure 13. Drag coefficient. [15]

- ✓ In Spain, Rodriguez [16] performed studies on a NACA 63418 airfoil using the FLUENT package, for a Re value of 430 000 for different roughnesses present in the airfoil to observe the influence of the roughness on the airfoil lift coefficient, obtaining the following results:

  - The first analysis shows how the lift coefficient of the airfoil decreases when it has a roughness of 0.5 mm compared to when it is clean. The figure shows the ideal condition obtained through FLUENT and in blue the effect of the dirt obtained experimentally.

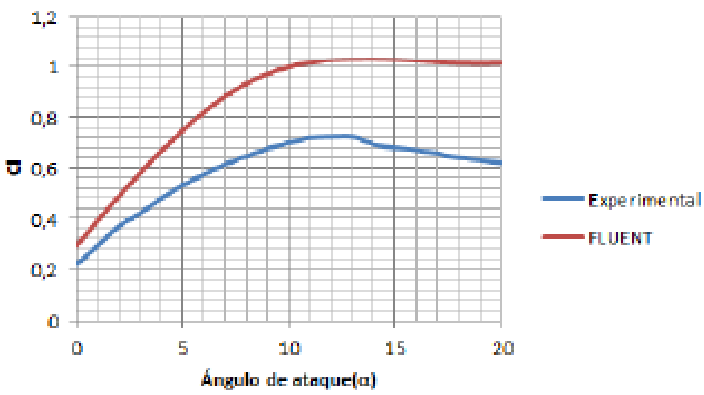

Figure 14. Lift coefficient of the airfoil. [16]

- In the second analysis, for the same value of *Re* and constant angle of attack, the behavior of the C_l of the profile is analyzed for different roughness heights. It can be seen in the graph as from the roughness value of 0.03 mm the C_l becomes practically constant.

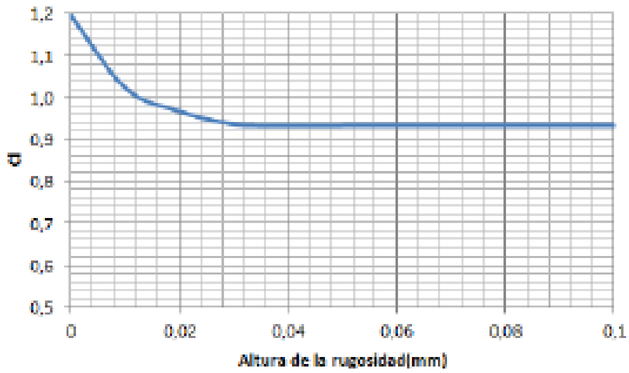

Figure 15. Lift coefficient for different roughness. [16]

✓ At the University of Windsor, Dalili [17] conducted several studies on the decrease in wind power output due to particles of different diameters that vary the roughness of the profile. In particular, they classified blade contamination problems into three distinct groups:

- In cold climates, *leading-edge icing* causes several problems, such as the total shutdown of the wind turbine, variation of the airfoil aerodynamics, and reduction of the material fatigue life.
- In humid climates and moderate temperatures, *contamination by insect impacts occurs*, in which case the insects remain adhered to the surface of the profile, causing erosion and the consequent modification of the aerodynamic properties of the profile.
- In dry climates, the most common is the *accumulation of sand particles on the surface*, causing a change in the roughness of the profile.

As a result of this analysis, they obtained several solutions to the problems previously discussed:

- For cold climates, the proposal is to use ice protection or de-icing systems, similar to those used in aircraft based on electrical resistances, in addition to modifying the materials used to build the blades.
- For insect collision, the proposed solution is to apply an anti-adhesive that repels insects from the surface of the shovel.
- In the case of blade erosion, the preventive solution is to place an elastomer on the leading edge of the wind turbine blades.

Wind tunnel studies

At Cairo University, Khalfallah [9] studied a 100 kW wind turbine and verified that the wind turbine operated within the normal parameters as indicated in the manual used for the test; the wind turbine under study consisted of three blades. In addition, they obtained measurements of the power delivered by the wind turbine in different measurement periods when it operates with dirt on its blades.

The performance of a wind turbine operating in air containing dust is affected because, at the leading edge of the wind turbine profile, dust particles accumulate along the entire blade. When the air speed around the blade

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increases, this accumulation accelerates, causing the wind turbine's power to decrease over time at the same speed. In addition, the boundary layer of the profile is affected since the dust particles generate roughness in the blade, causing the boundary layer to be modified. Thus, the overall efficiency of the blade is affected, resulting in a loss of power, as illustrated in Figure 17. Figure 16:

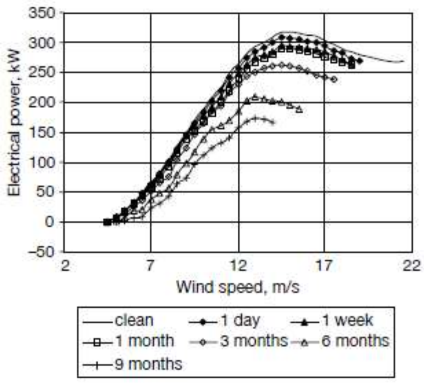

Figure 16. Electrical power vs wind speed. [17]

During the performance of these tests for several measurement periods, the blades were not cleaned, and the wind turbine continued to operate with the accumulated dirt daily.

It can be observed that the power decreases as the measurement period is more extended, and this is because the dust layer accumulated on the blades is getting thicker and thicker.

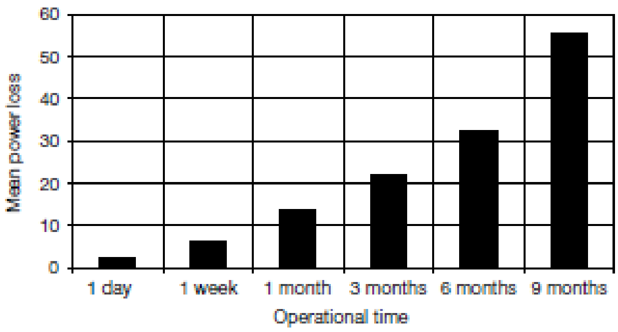

Figure 17. Power loss as a function of time. [17]

They also studied the effect of the diameter of the dust particles accumulated on the blades; the larger the diameter of the particles, the more significant the power drop.

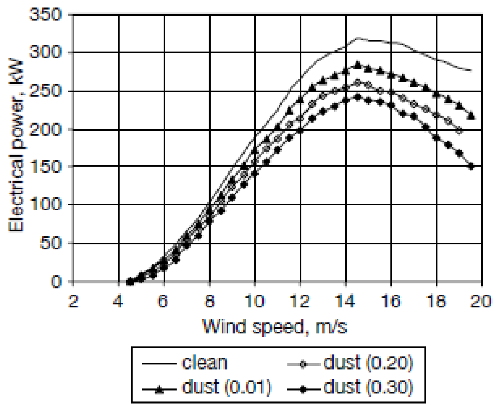

Figure 18. Electrical power vs particle diameter. [17]

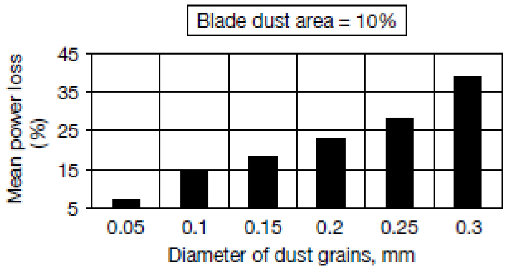

Figure 19. Power loss as a function of particle diameter. [17]

On the other hand, they also studied the effect of the percentage of the blade chord covered by dust particles on the power delivered by the wind turbine.

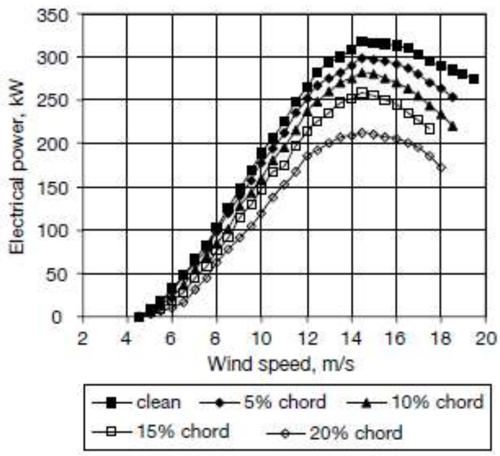

Figure 20. Electrical power vs percentage of chord. [17]

<u>Effect of Roughness on Wind Turbine Blades</u>

As described above, wind turbine blades are affected by different phenomena such as accumulation of dust or sand, freezing of the leading edge, and impact of insects on the blade surface; these phenomena cause variations in the roughness of the wind turbine blade profile, which can be summarized in two main issues:

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Modifications on the profile boundary layer: delay in the laminar-turbulent transition.

The Reynolds number defines the type of flow that an airfoil will have; if the *Re* is low (*Re* < 2000), there are laminar flows. If the *Re* is very high, there are turbulent flows. As for the boundary layer in general, there is a laminar-turbulent transition; several factors, such as the roughness change in the airfoil, heating or gusty wind can modify this transition.

Mueller [19] has conducted numerous studies on the laminar-turbulent transition in low Reynolds airfoils that will help us understand this phenomenon. The study indicates how by varying the angle of attack of the airfoil under study, this transition occurs closer and closer to the leading edge of the airfoil, as shown in Figure 22.

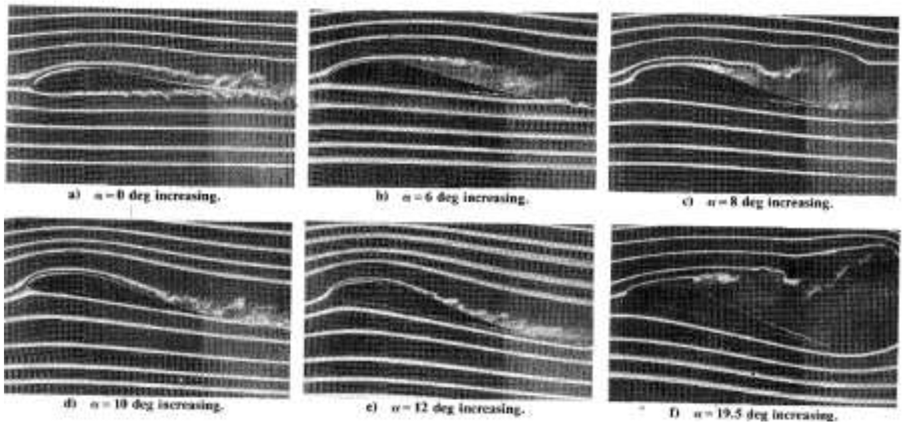

Figure 21. Flow around an airfoil [19].

He has also studied the transition of the laminar separation bubble in low Reynolds number profiles. He found that they present a laminar separation bubble for low angles of attack [20].

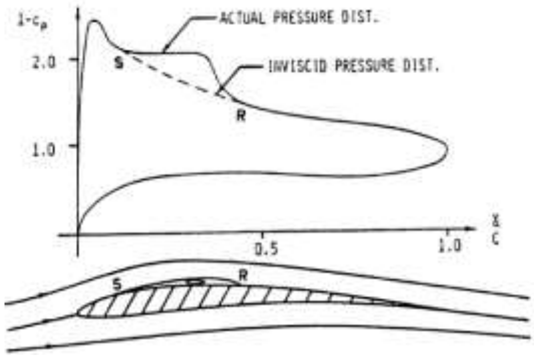

Figure 22. Leading edge bubble [11].

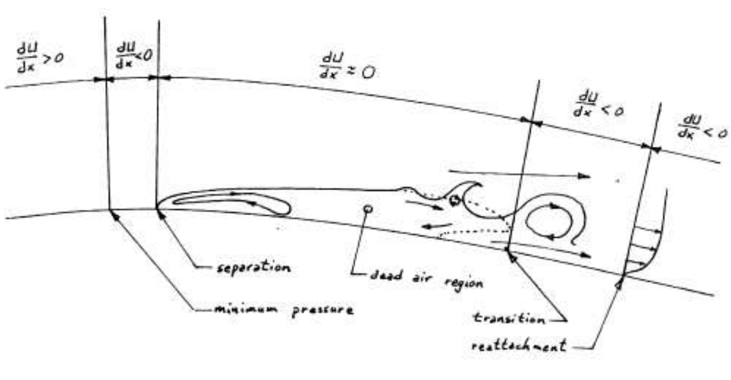

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Figure 23. Characterization of the flow around an Eppler profile [20].

2. Materials and Methods

This paper proposes to test the wind turbine with different roughnesses (located on the inside and outside) on its blades to evaluate the wind turbine conditions and compare them with an ideal wind turbine condition, i.e., clean.

For this purpose, different roughnesses will be generated on the wind turbine blades by sticking different types of sandpaper on them. First of all, the ideal position to place the different types of sandpaper will be analyzed, defining the percentage of the chord that the roughness will occupy on the blade in each test; then, each of the sandpaper to be used in the tests will be characterized, indicating their diameter and the weave they have.

To define the position of the roughness on the blades, it is known that dirt is generally located on the leading edge, being this the place where dust particles, snow in some cases or insects are impregnated. In order to define the percentage of the chord covered by the dirt, the wind turbine was tested by covering its blades with sandpaper of different weaves on both the top and bottom surfaces, highlighting that the transition from laminar to turbulent flow occurs on the top surface. The profile of the wind turbine blades tested is a low Reynolds profile; the transition point can be delayed or advanced by roughness on the blade surface. Taking into account the above mentioned, the following percentages of the chord covered with roughness were used:

Figure 24. Roughness up to 15% of the chord

Figure 25. Roughness up to 25% of the chord

Figure 26. Roughness up to 40% of the chord

The transition from laminar to turbulent boundary layer depends on the Reynolds number; when performing the calculations, it was obtained that in the operating range of velocities, the transition, these coordinates are outside the length of the wind turbine blade so that the flow will be laminar.

Sandpaper of different grits and grit sizes was used in the tests:

Table 2. Sizes of sandpaper grits

GRANO	TYPE OF SAND
from 100 to 120	Media
from 240 to 400	Very fine

The grits mentioned above were chosen because of the similarity of the grain size with the standard operating conditions of wind turbines and the kind of dirt that accumulates on their blades: the fine grit resembles the grain size of dust and sand, the medium grit resembles the grain size of coarse sand and that generated by the encrustation of insects. The roughness of the sandpaper to be used is:

- ✓ Very fine sandpaper: Use #320 sandpaper.

  k = 0.801 mm

- ✓ Medium sandpaper: A #100 sandpaper will be used.

k = 1,433 mm

Working Reynolds Number Analysis

In order to determine the friction factor present in the wind turbine blades, it is necessary to know the Reynolds number at which the turbine is working. When analyzing the Reynolds number, it is concluded that the flow is turbulent in all cases. Once the Reynolds number is obtained, it can be indicated that the thickness of the boundary layer will be between 10^{-2} and 10^{-1} mm as it is a laminar boundary layer.

Knowing the absolute roughness in each case and the thickness of the boundary layer, it is possible to indicate the type of flow that will occur in each case.

- ✓ Very fine sandpaper: #320

  k = 0.801 mm

- ✓ Medium sandpaper: A #100 sandpaper will be used.

  k = 1,433 mm

In the cases analyzed $\delta < k$; therefore, the flow will be *hydraulically rough.*

In summary, the following can be said: the flow is turbulent and hydraulically rough in all cases, the boundary layer becomes turbulent as the roughness is higher than the boundary layer thickness, and the friction factor does not depend on the Reynolds number; it depends only on the relative roughness.

Wind Turbine RPM and Torque Measurement

In the development of the present study, it was desired to obtain the measurements of torque and rpm generated by a wind turbine when operating in different conditions of roughness in its blades, both roughness height and affected surface.

The low-power wind turbine tested is shown in Figure 4, and presents the following characteristics:

Type: Synchronous induction generator

Axis: Horizontal

Nominal Power: 800 W

Rated Working Speed: 1000 rpm

Rotor: Permanent magnets

Number of poles: 14

Propeller type: 3 blades

Propeller diameter: 1,47 m

Coupling: Direct coupling without gearbox

Blade material: Reinforced plastic

Power Control: Passive Type

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Figure 27. Three-bladed wind turbine

In order to obtain the torque and rpm measurements, it was necessary to modify the shaft that supports the wind turbine blades to attach a rotating torque meter as a measuring instrument to analyze the aforementioned parameters. Therefore, an extension of the shaft that connects the generator to the blades was made, including flexible couplings, the torque meter and the rotor wheels. The final modifications are shown in Figure 28.

Figure 28. Schematic of the modifications made

In order to control the Reynolds number and the rpm of the wind turbine during the tests, to avoid resonance phenomena and affect the measurements, a load impedance is placed in the test circuit at the wind turbine output through the connection of a resistor bank, and a rectifier bridge of electric current will also be placed. The connection to be made in the resistor bank is explained in Figure 6. In addition, a voltmeter will be connected in parallel with the resistor to measure voltage.

The rectifier bridge is an electronic component with 6 diodes for maximum current values of 35 A and a voltage of 1600 V. A load impedance of 0.8 Ω will be used.

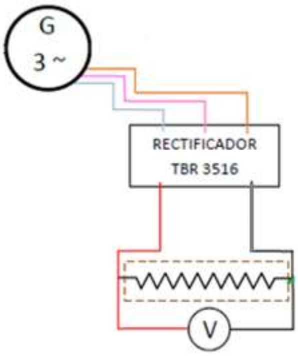

Figure 29. Load impedance connection

The wind tunnel used in the tests is 2.55 m wide and 1.83 m high; it is an open tunnel with a closed circuit. The area ratio between the tunnel and the element to be tested is 0.36.

The first step of the measurements is the clean measurement. For the velocity measurement, a pitot tube was placed at the height of the wind turbine axis, at a perpendicular distance, at a diameter (D) approximately so that it can be considered as the velocity of the free current (U_∞). Next, updrafts and downdrafts were performed by increasing the tunnel velocity from 0 m/s to 15 m/s with 1 m/s increments.

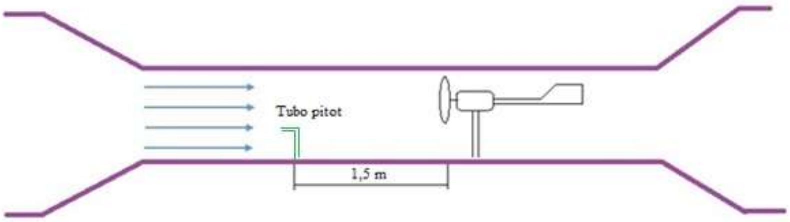

Figure 30. Wind tunnel velocity measurement.

During the measurements, the following parameters will be obtained: electrical power, the torque delivered by the wind turbine, air density, air temperature, rotor area, wind speed, and length of the wind turbine blades; in order to obtain comparative graphs of the Torque Coefficient vs Speed, Power Coefficient vs Speed.

Wind Turbine Measurement with Different Roughness Heights ad

Two different types of sandpaper were used for this test, providing different roughness heights, as well as three different configurations of the percentage of the blade covered by the roughness:

- Roughness 320-15%.
- Roughness 320-25%.
- Roughness 320-40%.
- Roughness 100-15%.
- Roughness 100-25%.
- Roughness 100-40%.

The wind tunnel tests are affected by several effects, mainly due to the blocking phenomenon that occurs when the area ratio is higher than 10%. Unfortunately, in the case under study, the area ratio reaches 36%, making it necessary to make corrections to the measured parameters.

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In the analyzed bibliography, corrections for the power coefficient (C_P) have been found by affecting the measured value by a blocking factor using the following expression:

$$C_{Pc} = C_{Pt}\left(\frac{U_t}{U_\infty}\right)^3$$

The C_{Pt} is the power coefficient obtained with the data measured in the tunnel, and the C_{Pc} is the corrected power coefficient.

For the correction of the torque coefficient (C_T), a blocking factor analogous to the previous one with the speed ratio squared will be used.

$$C_{Tc} = C_{Tt}\left(\frac{U_t}{U_\infty}\right)^2$$

To measure the torque and rpm, the torque meter software was used for one minute at a frequency of 20 Hz, thus obtaining groups of data which, when processed, gave a normal distribution. To give validity to the measurements obtained, the skewness and kurtosis of each group of data were calculated; in all cases, the skewness did not exceed the value of 0.05, and the kurtosis always exceeded the value of 3, so the data are considered valid since they represent a normal distribution concentrated on the mean value; therefore, the mean was used as a representative value. The mean of each group of values was used as the only value to obtain the curves presented in rpm.

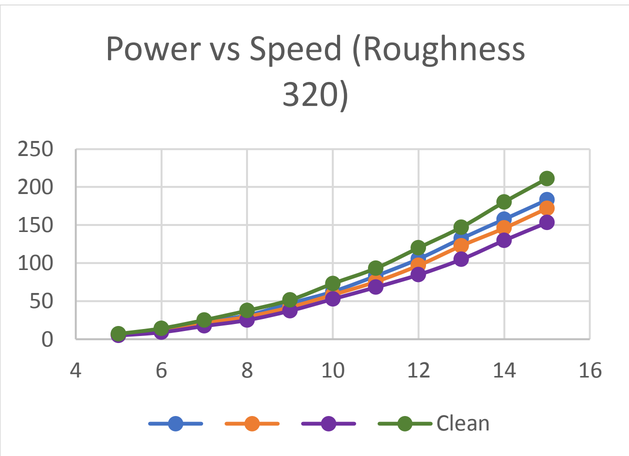
3. Results and Discussion

For the clean wind turbine, once the corrections have been made, the maximum electrical power is 211 watts; and the maximum value of the Power Coefficient is 0.06. Similar to the case of the Electrical Power in the Torque and the Torque Coefficient, a decrease in the values is observed when the correction coefficient is applied. The maximum torque value reached is 4.6 Nm for the Torque Coefficient of 0.051.

<u>Wind Turbine with Different Roughnesses</u>

- *Electrical Power*

The following figures show the results obtained with the different roughness configurations tested. The results have been corrected with the corresponding block coefficient.



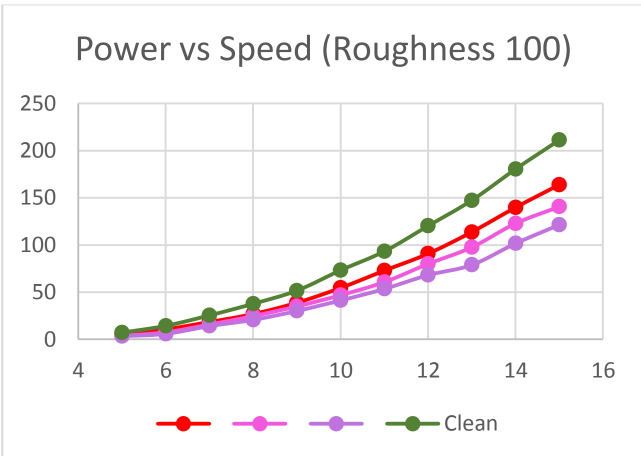


Figure 31. Power vs Speed. Wind Turbine with Roughness 320 **Figure 32.** Power vs. Speed. Wind Turbine with 100 % Roughness

It can be observed that the electrical power decreases when the percentage of rope covered by roughness increases and when going from a lower to a higher roughness. For example, in the case of Roughness 320 (very fine), the maximum power is 153 watts, and for Roughness 100 (medium), the maximum value is 121 watts, contrasted with the 211 watts obtained from the clean wind turbine.

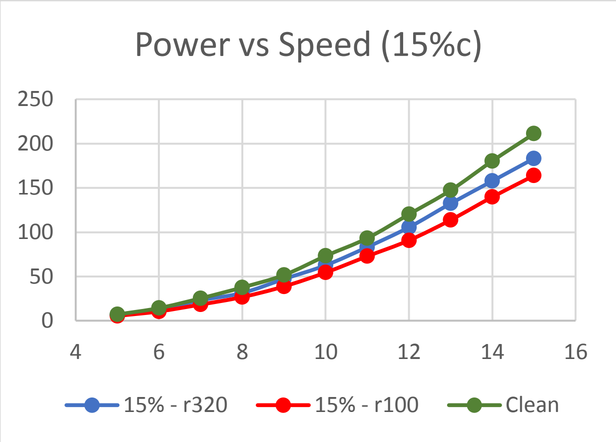


Figure 33. Power vs velocity for different roughness with 15%c.

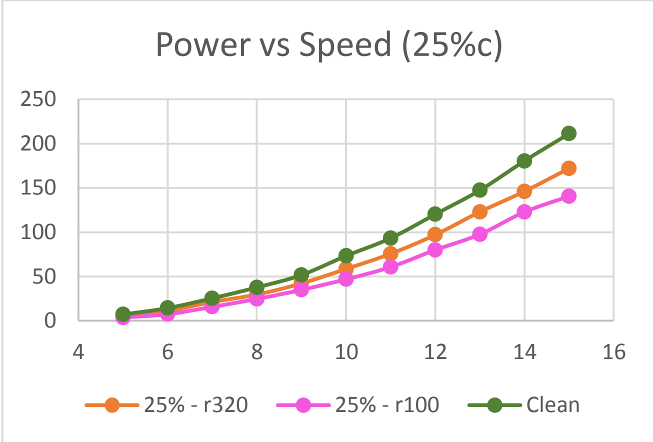


Figure 34. Power vs velocity for different roughness with 25%c.

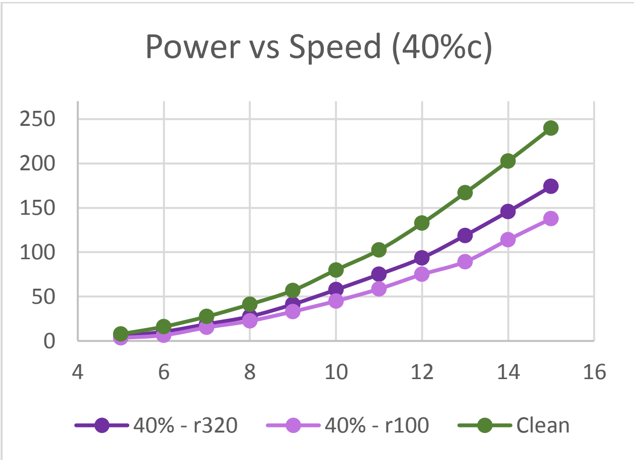


Figure 35. Power vs velocity for different roughness with 40%c.

At low speeds, the difference is not noticeable in absolute value, but as the speed increases, the differences increase according to the two factors analyzed: Percentage of rope covered by roughness and Roughness (Very fine or Medium).

In addition, analyses were performed on the percentage differences obtained in the electrical power measurements, always contrasted with the nominal condition, and the following results were obtained:

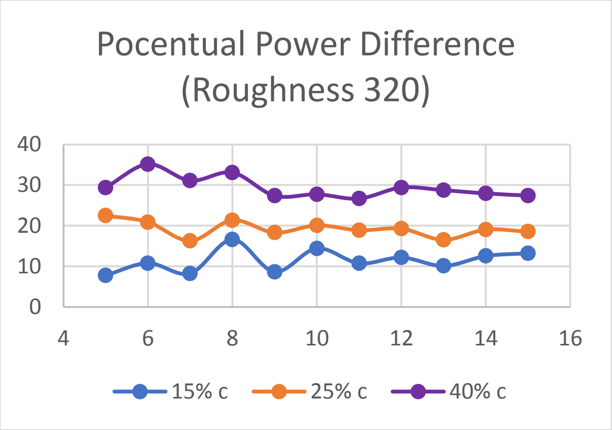


Figure 36. Percentage difference of electrical power. Roughness 320.

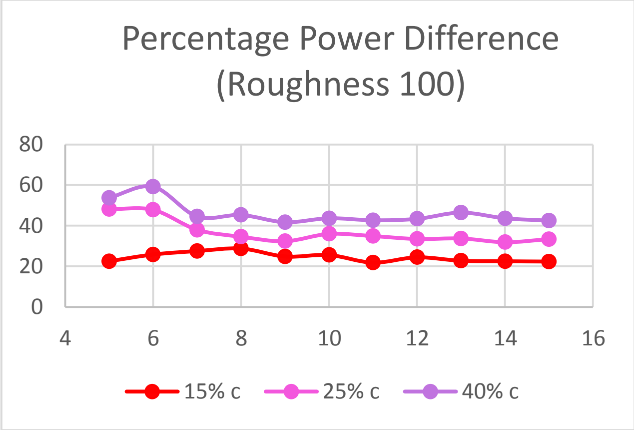


Figure 37. Percentage difference of electrical power. Roughness 100.

From the cases analyzed, the percentage difference between each of the cases analyzed for the nominal condition is greater when the roughness and the percentage of the chord covered increases. This difference is better appreciated at high speeds, as is the case analyzed for 15 m/s; the highest percentage difference obtained for the nominal condition is given for Roughness 100 (average), with 40% of the chord covered by roughness. In this case, the difference is 42.52 %.

- *Power Coefficient*

For the analysis of the Power Coefficient, the same comparison parameters were used as in the case of Electrical Power, and the following results were obtained:

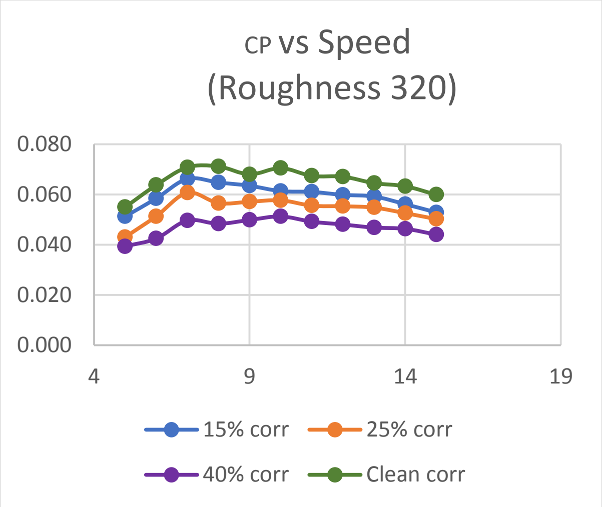


Figure 38. C_P vs Speed. Wind Turbine with Roughness 320

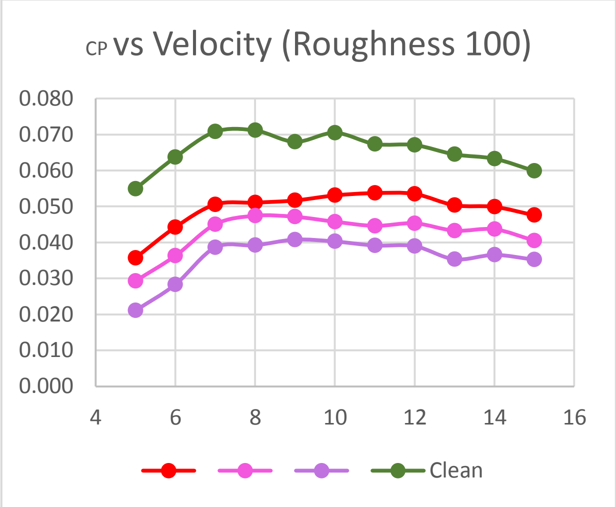


Figure 39. C_P vs Speed. Wind Turbine with Roughness 100

In this case, the Power Coefficient decreases with increasing roughness, 320 to 100 and with an increasing percentage of chord covered by the roughness.

When comparing the Power Coefficient, for Roughness 320, the maximum value of 0.044 was obtained, and for Roughness 100, 0.035 was obtained, which are lower than the 0.06 obtained for the clean condition.

- *Torque*

Similar to the case of the electrical power in the Torque and Torque Coefficient, a decrease in the values is observed when the correction coefficient is applied. The maximum torque value reached is 4.6 Nm for the Torque Coefficient of 0.051.

The following figures show the results obtained for the torque values using the same division criteria as for power.

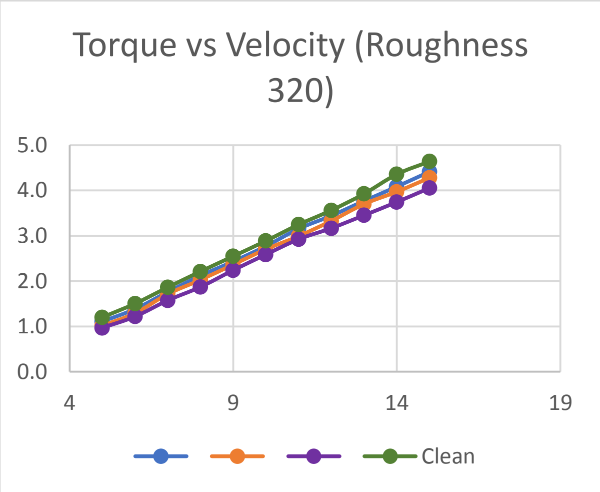


Figure 40. Torque vs Speed. Wind Turbine with Roughness 320

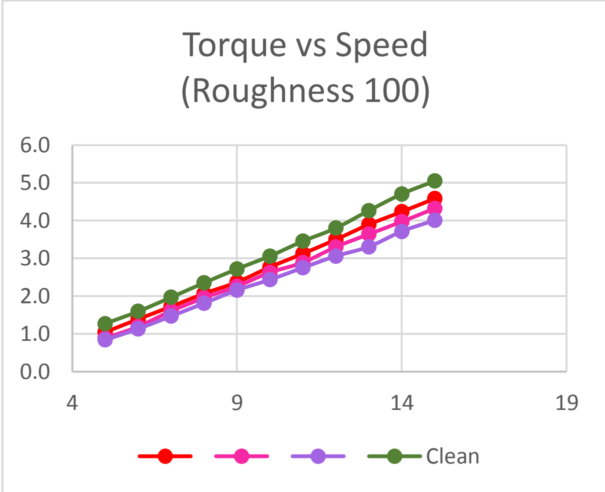


Figure 41. Torque vs Speed. Wind Turbine with 100 % Roughness

It can be observed how the torque values decrease when the roughness and the chord percentage increase. The maximum torque values obtained can be compared; for Roughness 320, the maximum value is 4.1 Nm; for Roughness 100, the maximum value is 4 Nm; while for the clean wind turbine, the maximum torque value is 4.6 Nm.

The torque values obtained for the same percentage of chords with different roughnesses are compared below:

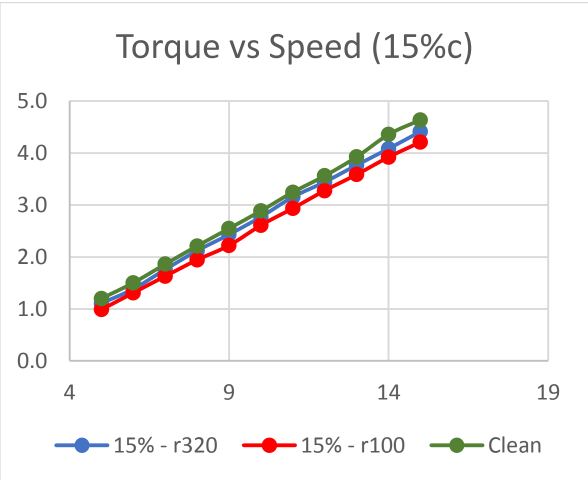


Figure 42. Torque vs velocity for different roughness with 15%c.

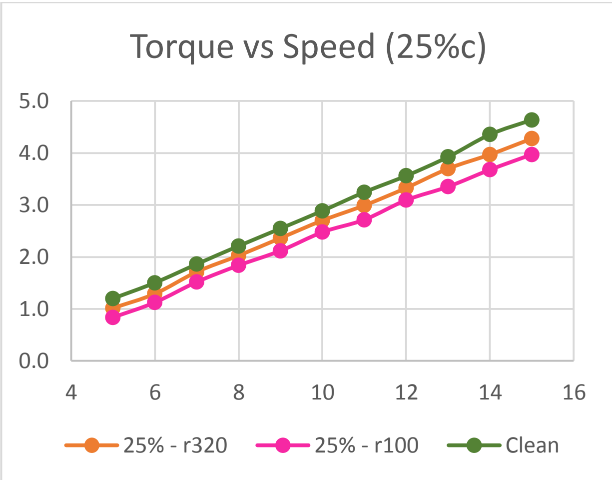


Figure 43. Torque vs velocity for different roughness with 25%c.

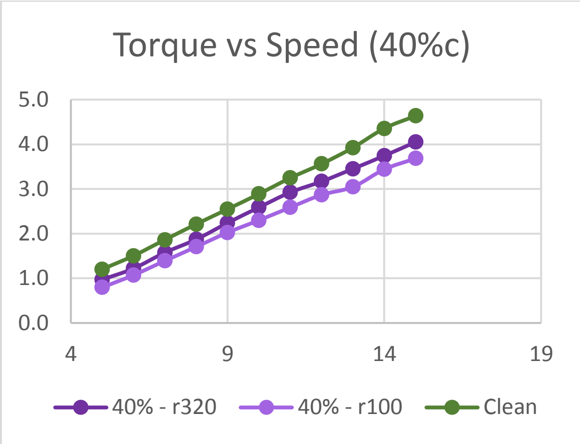


Figure 44. Torque vs velocity for different roughness with 40%c.

As in the case of power, an analysis was made of the percentage difference in each case for the nominal condition, resulting in the following:

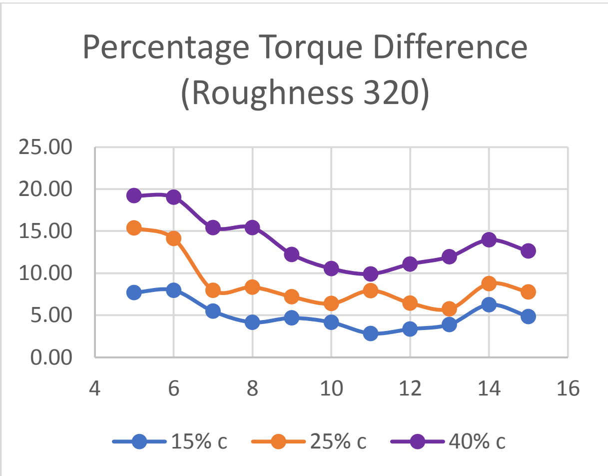


Figure 45. Percentage difference in torque. Roughness 320

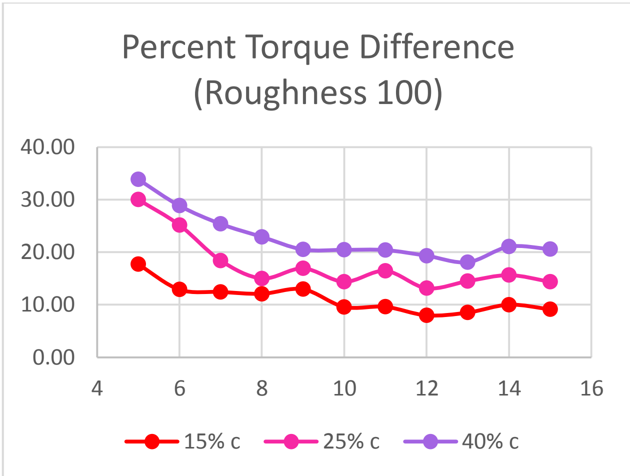


Figure 46. Percentage difference of torque. Roughness 100.

In all cases, the highest percentage difference for the nominal condition is observed when the maximum percentage of the chord (40%) and the highest roughness (100) are combined. Thus, the highest torque difference for the nominal condition reaches 20.58%. On the other hand, when increasing the free current speed, it is observed that after 8 m/s there is a break in the graphs from which the differences remain practically constant.

- *Torque Coefficient*

For the torque coefficient analysis, we proceeded similarly to the power coefficient, comparing each roughness with the different percentages of a chord. The results are presented in the following figures:

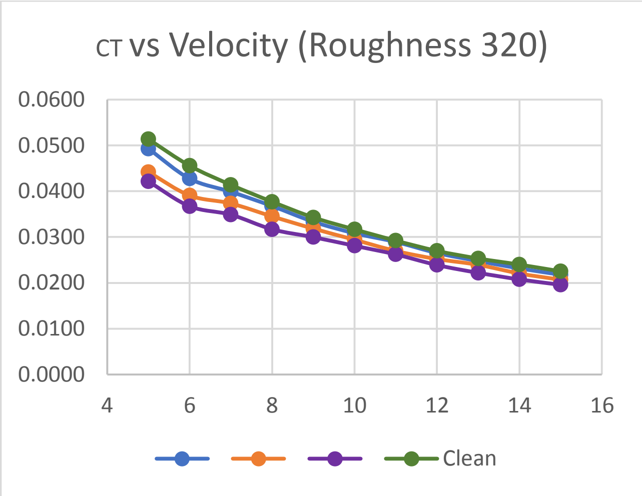


Figure 47. C_T vs Speed. Wind Turbine with Roughness 320

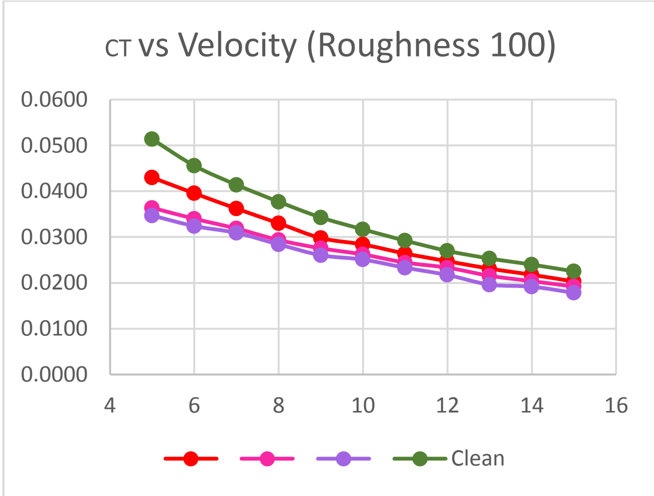


Figure 48. C_T vs Speed. Wind Turbine with Roughness 100

In this case, it is possible to appreciate the decrease of the Torque Coefficient for the clean condition when the analysis parameters are modified: chord percentage and roughness.

- *Measurements with RPM*

As for the torque and power curves for the wind turbine, it was observed that the wind turbine only delivers the power and torque according to the RPM at which it rotates, so they are not included in this work.

In addition, the speed measurements were contrasted with the RPM, obtaining the results shown below:

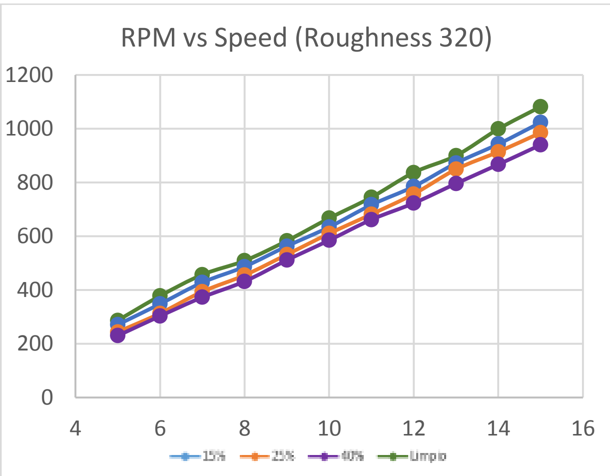


Figure 49. RPM vs. speed. Roughness 320

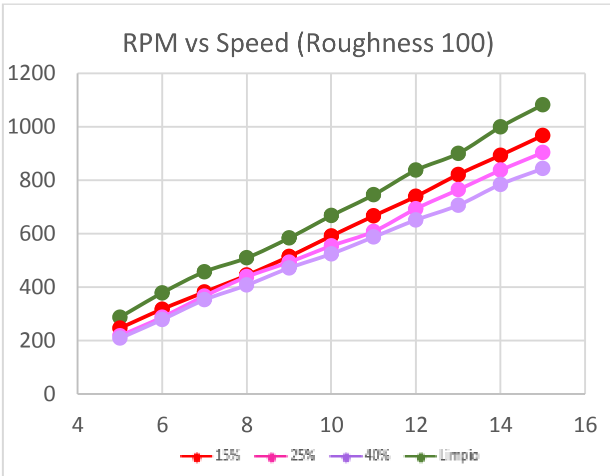


Figure 50. RPM vs. speed. Roughness 100

In the previous figures, it can be observed that the RPM also decreases when the roughness and the percentage of rope covered by it increase; in this way, the data obtained previously for Power, Torque, Power Coefficient and Torque Coefficient can be corroborated; since if we observe the wind turbine operation curves, it delivers less power and torque as the RPM decreases.

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- *Reynolds number*

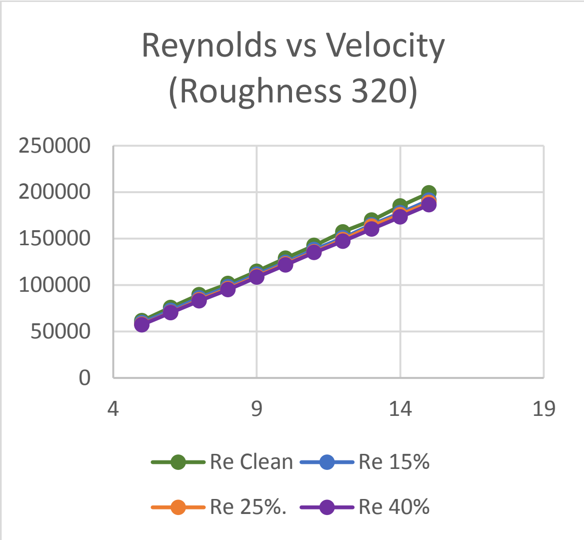

Figure 51. Reynolds Number for Roughness 320

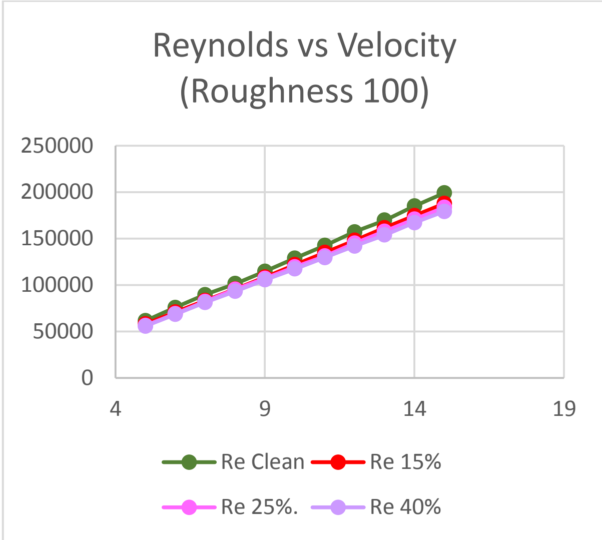

Figure 52. Reynolds Number for Roughness 100

In all the tests, Reynolds numbers between 57,700 and 198,900 were used, which can be considered low Reynolds numbers.

Recalling the graphs for percentage differences in electrical power and torque, a greater percentage difference can be observed at low speeds (5, 6 and 7 m/s).

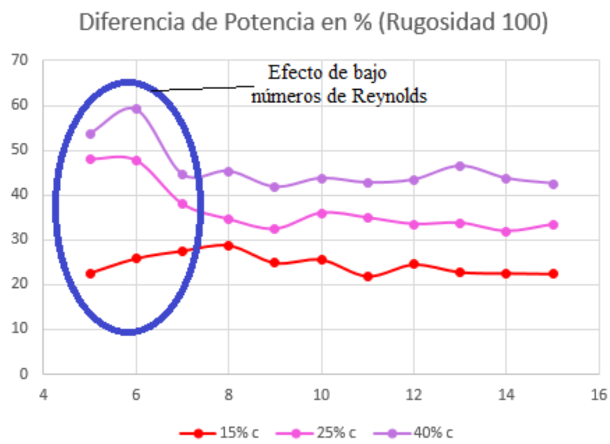

Figure 53. Effect of Reynolds number at low speeds.

This effect can be attributed to several causes:

- ✓ At low speeds, the Reynolds number is lower. In that case, the viscous effects are evidenced by the roughness in the blades, which means that much less power or torque is needed for the nominal condition since the resistance increases due to the roughness, which helps at start-up.

- ✓ Due to the implementation of sandpaper on the wind turbine blades for the tests, in addition to generating roughness, the blade's geometry was affected since the leading edge did not remain completely rounded.

- ✓ At the speed of 8 m/s, the Reynolds numbers for all the cases analyzed are around 100 000, which is a typical Reynolds number for the motion of a small aircraft except in areas close to the boundary layer. This value of the Reynolds number indicates that the viscous forces are 100 000 times smaller than the convective forces, and therefore, those can be ignored. The Reynolds number at speeds of 5, 6 and 7 m/s has a value of less than 100 000. Therefore, the larger percentage difference from the nominal condition can be attributed to viscous and convective forces.

4. Conclusion*s*

From the measurements made in the wind tunnel, it was possible to characterize the wind turbine as clean, assuming it was nominal. For this condition, the following maximum values of the measured parameters were obtained:

- Electrical Power: 211 Watts
- Power Coefficient: 0.06
- Torque: 4.6 Nm
- Torque Coefficient: 0,051
- RPM: 1082

In the clean condition, two velocities were measured in the tunnel, one corresponding to the tunnel alone and the other to the tunnel with the wind turbine. These were later used to obtain the correction factors due to the blockage phenomenon.

When comparing the data of Electrical Power, Power Coefficient, Torque and Torque Coefficient of the different conditions tested for the nominal condition, it was observed that the values decrease with the two factors analyzed: The percentage of chord covered by the roughness and the type of roughness. Furthermore, of the two factors analyzed, the change of roughness generates more noticeable effects since when comparing the data at the same percentage of chord with different roughnesses, greater differences are obtained than when the percentage of chord covered with the same roughness is increased.

As mentioned above, the effect produced by the dirt on the blades translates into a change in roughness that affects the performance of the wind turbine since it delivers less power and less torque, and its rotational speed decreases.

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