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## **EXPERIMENTAL AND NUMERICAL STUDY OF DIFFUSER AUGMENTED WIND TURBINE - DAWT**

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### **ABSTRACT**

In this work was studied the effect of a shrouded structure around a small wind turbine. The objective was assessing the induced increment on their productivity, evaluating power coefficient. Laboratory measurements showed that improvements were obtained on electrical output, resulting in a maximum increase of 120 %. Measurements showed a power augmentation by a factor about 1.5-2.3, compared with the rotor without the shroud. Where a more pronounced augmentation is achieved at lower velocities. These increments attained, comparatively with previous studies, are shown in the same order of magnitude. Whereas an enhancement more pronounced relative to previous studies made for distinct shroud designs. Numerical simulations implemented in ANSYS FLUENT, modelled the rotor performance describing a non-similar trend on their respective power coefficients, comparatively with those obtained in experimentally. CFD calculations were performed at flow ( $Re=25343$ ) with values of 6 and 14 m/s to the C-D device. CFD calculations performed an evaluation of the velocity experienced in the action rotor zone, which provided maximum increase of these air velocities of 81 % and 86 %, respectively.

**Keywords:** wind, CFD, ANSYS, experimental tests, fluid simulation.

### **INTRODUCTION**

Day by day electricity becomes a decisive factor on the growth of economics and sustainable development. Thus, synergies with best practices should be established for its production. To be part of the solution, small wind turbines, must to accommodate increases in their energetic performance. Therefore, in this work, improvements on the energy production of small wind turbines were studied.

A mechanism to increase power output can be applied placing an annular lifting device around the rotor. This device is known as a shroud or a diffuser of annular wing. The increase in diffuser exit plane velocities combined with a reduction of static exit pressure and consequently is obtained an enhanced of mass flow leading to a higher extraction of energy potential. Furthermore, the suction effect is related to the lift of the airfoil and according to the Kutta Joukowski theorem (Batchelor, 1968), related to the bound vorticity. The annular airfoil generates a radial lift force creating a ring vortex, based on Bio-Savart law (Anderson 2001), that consequently will induce a higher velocity on the suction side. Furthermore, this higher velocity enhances the mass flow through the rotor plane (Ten Hoopen, 2009).

In order to take advantage of mixing effects flanged applications on shroud plays an important role. This flanged, also known as brim, collects and accelerates the approaching wind (Ohya

*et al.*, 2008). The flange is placed at the exit plane of the shroud, such as in Figure 1, and mimics the Guerny flap used in F1 racing cars (García-Abril, 2014).

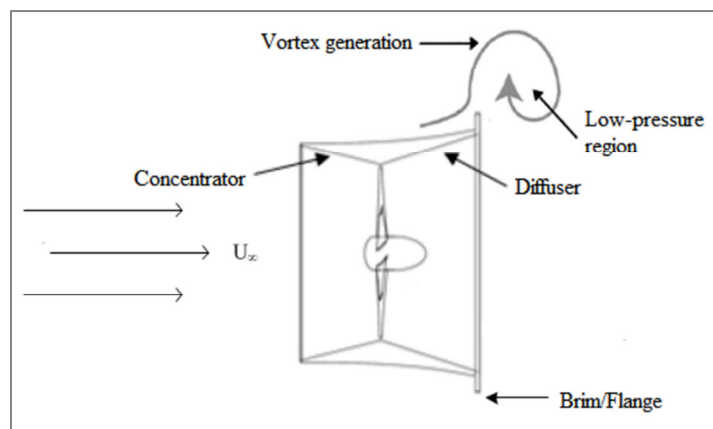


Fig. 1 - Schematic system representation composed by a concentrator-diffuser (C-D) and a wind turbine (WT), adapted from Ribeiro *et al.* (2013) and Ohya *et al.* (2008)

The flange is a structure ring-type plane with a variable height may affect the shroud performance. (Ohya *et al.*, 2008, Kosasih and Tondelli, 2012).

As can be seen from Figure 1, the flange induces a low-pressure region in the near wake of the diffuser by vortex generation. Furthermore, more mass flow is drawn to the inside of shroud (Ohya *et al.*, 2008, Ohya and Karasudani, 2010, Takahashi *et al.*, 2012). The flange causes vortices formation, an enhancer in the pressure drop and, consequently, an increase the air speed of the outlet. An increase the air velocity in the diffuser, is therefore, achieved (Mansour and Meskinkhoda 2014).

Potential of ducted / diffuser wind turbines was acknowledged first by Betz (1929), as reported by Ten Hoopen (2009). The idea of DAWT in a preliminary study were proposed again by Lilley *et al.*, (1956). The work from Lilley *et al.*, (1956) the increase in axial velocity and reduction of blade tip losses was described as been as the main factors to enhance the power. A creation of a flow augmentation was also suggested where laying of a flap at diffuser exit plane would raise the power increase.

Experimental studies performed by Igra (1981) shown that power enhancement of a shrouded wind turbine is described as been as a direct consequence of the sub-atmospheric pressure created around the rotor and at the exist plane of the diffuser. These sub-atmospheric pressures generate one effect of suction that produces a higher mass flow. Also is depicted that up to 80 % improvement in the shroud power augmentation can be obtained.

Bet and Grassmann (2003) developed a shrouded wind turbine with a wingprofile ring structure. An increase in power output by the wing system of 2.0 was obtained, reproducing an increment of 100 % relatively to conventional wind turbine. Additionally, Grassmann *et al.* (2003) continue the work performing some experimental measurements using a non-optimized wind turbine. The increase of power output in a factor of 55 % for high wind speeds and 100 % at low wind speed was described. Moreover, based on CFD simulations at 5 m/s it was concluded that shroud it's responsible for an increment in power output of 1.52 times higher than standard wind turbine.

A frustum-shaped diffuser was proposed by Matsushima *et al.* (2006) based on economic standpoint and wind speed distribution. The effect of diffuser's prototype shape has

confirmed that the power output of the generator increased by up to 2.4 times compared to that of a conventional turbine.

Wang *et al.*, (2008) investigated convergent-divergent scoop effect on the power output applying on small wind turbine. Results shown that the scoop increases the airflow speed and enhance the power output 2.2 times relative to conventional wind turbines. These results also indicate that electricity yield can be improved at lower wind speeds.

Ohya and Karasudani (2010) described a remarkable increment in the output power. This, significant increase, is induced by the low-pressure region, that generates a zone of strong vortex formation behind the broad brim that draws more airflow to the wind turbine inside the diffuser. Conducting field experiments using a wind turbine prototype of 5 kW, where was obtained an increase in power output of 2.5 times superior than bare wind turbines. Also wind tunnel measurements were made, leading to increments in power coefficient range between approximately 90 % and 140 %, reporting a significant enhance in the output power coefficient approximately 1.9-2.4 times as large as a bare wind turbine.

Kosasih and Tondelli (2012) performed experimental studies of shrouded micro wind turbines. Experimental measurements of coefficient performance shown an increase of 60 % in addition of a simple conical diffuser, and 63 % with the addition of nozzle - conical diffuser shroud compared to the performance standard small wind turbines. Moreover, it can be stated that the work from Kosasih and Tondelli (2012) leads to an increment of 1.6 times higher relative to that obtained with a conventional turbine. Furthermore, it's described how the diffuser length and brim height can affect the performance augmentation of micro wind turbines.

Toshimitsu *et al.* (2008) performed flow velocity measurements with flanged diffuser by Particle-Image-Velocimetry. Results have shown that turbine blades rotating effects suppress the turbulence and the flow separation near the inner diffuser surface. At diffuser downstream some vortices, was consistently found such as, one behind the flange acts suction effect on wind to the diffuser, consequently raise the inlet flow velocity. Hence, diffuser device enhances the wind power in 2.6 times relative to standard wind turbine.

Aranake *et al.* (2014, 2015) performed some numerical analysis of shrouded wind turbine configurations, and a low ratio between shroud radius to shroud chord length of the diffuser is desirable, this indicate that the benefit of introducing shroud to a wind turbine is more easily to realize in small wind turbines, where this ratio is feasible. Likely verified in previous works, the shroud can be used effectively at low cut-in speeds and offers improve on the energy capture. Improvement in power extraction beyond the conventional turbine were achieved, at  $U_{\infty} = 5$  m/s is shown an improvement in power output by a factor of 1.93 and 3.39 for different shroud models relative to conventional wind turbines.

Main idea of Enhanced WT is enhance the productivity of urban wind turbines. Therefore, enhanced is achieved by encapsulating the wind turbine, accelerating the air flow and thus creating more electric energy.

Enhanced WT is composed by a convergent - diffuser and a wind turbine, as can be seen in Figure 1. Also, at diffuser exit plane is accommodated a brim/flange, in order to exploit the suction effect.

Associated with the project Enhanced WT some research activities have been developed. The work from Ribeiro *et al.* (2013) shows the preliminary results of the alternative design of the convergent-divergent. This annular structure was optimized in CFD simulations and wind

tunnel measurements. Results shows that up to 124 % improvements in power output with C-D can be obtained.

According with García-Abril (2014), numerical studies were performed for enhance the performance, optimizing the diffuser outlet angle. Despite of several angle have been studied, the 25° (without roughness) and 27° (with roughness) was considered those that enhance the power. These models suggest an improvement of 3.6 % to 8.7 % relative to an initial model (20°). As noted previously this study also concluded that the use of shrouded rotors induces a suction effect due to a pressure gradient generated in outlet of C-D.

Associated with the development and investigation of the research project Enhanced WT was created and tested a prototype. Presently, this project is in final prototype phase and soon pre-industrial series will accommodate some progress.

## METHODOLOGY

### Experimental

Evaluations of the generated electricity were performed in subsonic wind tunnel for different wind speeds. Application of wind turbines in urban setting are primarily characterized by the operating at low wind speeds, as such, more importance was given to these speeds. The wind turbine scaled model was tested in the wind tunnel for the following wind velocities: 6; 7; 8; 10; 12; 14; 16 m/s, ranged from  $47143 < Re < 125714$ .

Corrections for a temperature value of 290:15 K and for an altitude of 600 m were made, in short, density of air was,  $\rho_h = 1.1337 \text{ kg/m}^3$ .

Experimental tests were made in an Armfield Limited model C2 Subsonic Wind Tunnel, as presented in Figure 2(a).

Physical dimensions of subsonic wind tunnel allow only to evaluate aerodynamically wind turbine models with reduced dimensions. Electric circuit diagram presented in Figure 2(b) was used in measurements of the electric power generated by wind turbine model.

It was applied a simple control algorithm, by ensuring a load variation. Throughout load variation it was feasible to identify the highest point of electric power produced by the wind turbine at each wind speed studied.

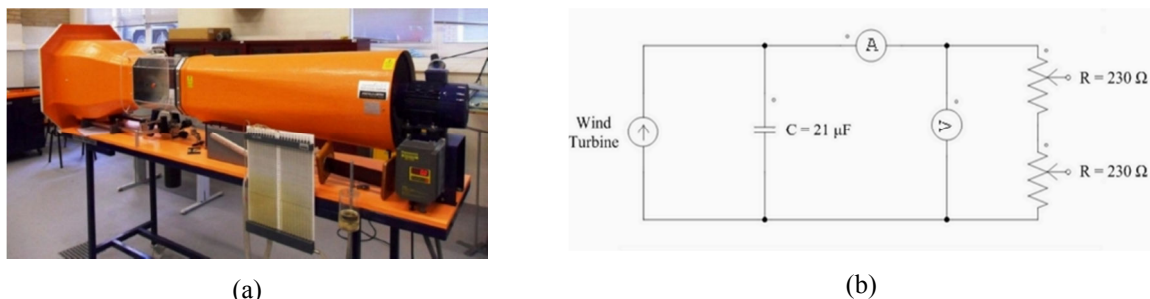


Fig. 2 - (a) Subsonic wind tunnel; (b) electrical circuit diagram used in experimental setup

In order, to enhance the electric performance of wind turbines, experiments in wind tunnel with a system composed by an encapsulated wind turbine were done. Encapsulated wind

turbine system is performed accommodating a C-D that surrounding the wind turbine, as can be seen in Figure 3.

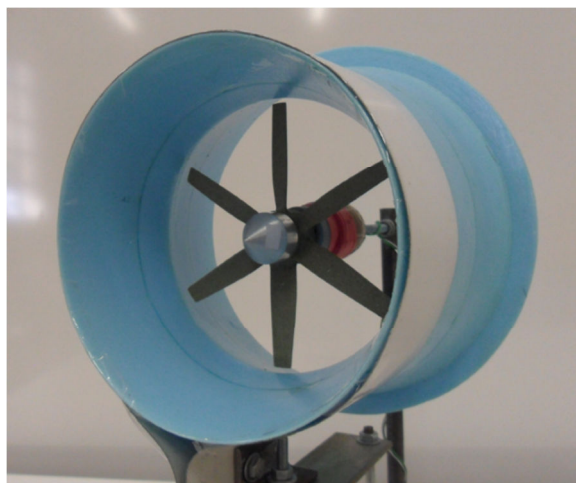


Fig. 3 - Representation of the scaled model implemented in experimental wind tunnel setup

It's worth noticing, that the models present a scale factor of  $L_r = 8:33$ . Table 1 presents the main design dimensions.

Table 1 - Main dimensions on the C-D model design

Part or Detail	Dimensions
C-D length	108 mm
Diameter at C-D center	108 mm
Brim/Flange size	10 mm
Concentrator angle ( $\alpha_i$ )	8°
Diffuser angle ( $\alpha_0$ )	16°

## Numerical

For perform an CFD 3D model, the following steps were considered applied by (Lanzafame *et al.*, 2013): Reproduction of the models using 3D CAD files; Generation of computational domain; Meshing of computational domain; Setting turbulence model; Defining the specifications of FLUENT solver and Post Processing results.

Wind turbine performance for the various rotational speeds and air flow conditions were studied using a 3D model that replicates the physical dimension of the aerodynamic model tested at wind tunnel.

Nevertheless, CFD calculations were performed to evaluate the effects that C-D device produces in air flow.

Wind turbine 3D CAD file was imported as parasolid form and an enclosure form was generated to ensure the surrounding air. A cylindrical domain with a radius of 0.2 m was created. Moreover, the distance of the rotor relative to the inlet and outlet of the domain, were

taken into account. Therefore, following Figure 4 produce current distance of 3D and 12D relative to the inlet and outlet boundary, was selected based on the work developed by (Carcangiu, 2008, Gomis, 2011, Mo *et al.*, 2013, Fleck, 2012).



Fig. 4 - Computational domain specifications, WT distance relative to velocity-inlet (B1) and with pressure-outlet (B2)

Was generated a tetrahedral mesh of, approximately, 1.3 million elements. Figure 5(a) shown the performed mesh.

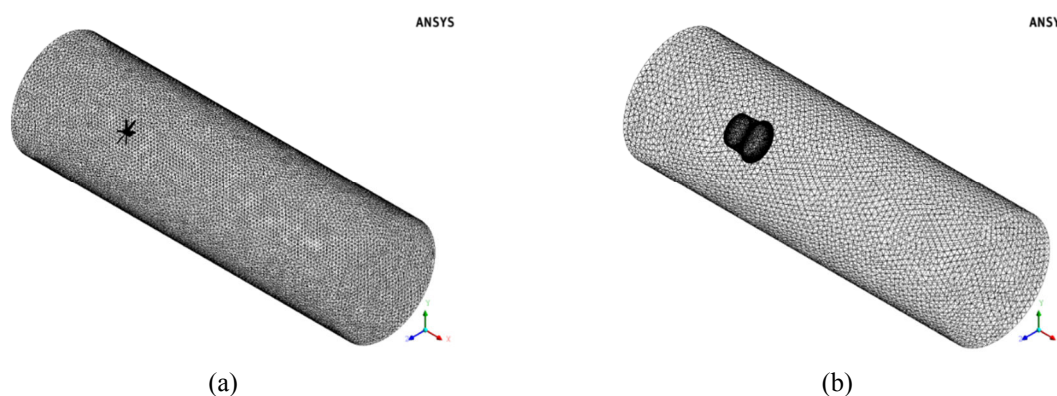


Fig. 5 - Computational mesh generated for the analysis of rotor performance

Upon the mesh generation, the three-dimensional Navier-Stokes equations are solved using a RANS approximation. A standard  $k - w$  model was used with the default options presented by the model on the software package (Wilcox, 1994).

As stated previously, CFD calculations were conducted to analysis of effects that C-D device generates in the air flow that surrounding the wind turbine. Therefore, C-D 3D CAD file was imported as IGES file and were reproduced the domain dimensions applied as in the case of wind turbine.

Subsequently, a tetrahedral mesh of approximately 2.8 million elements was produced. Figure 5(b) presents the performed mesh.

Turbulence modulation effects as previously a standard  $k - w$  model were used (Wilcox 1994). In order, to increase the computing power a parallel processing was applied where 4 CPU were used. A pressure-based solver with a transient formulation was applied with a density of the air  $\rho_h = 1.1337 \text{ kg/m}^3$ .

Regarding to the modulation of the rotational effects, on this work the moving reference frame was implemented. To setup the frame motion model, the unit vectors and origin of the rotation axis were imposed. The cell zone condition was set up by imposing the rotational velocity in the absolute specification. Throughout, a tip speed ratio equal to  $\lambda = 2$ , were considered the optimal values of angular speed rotor shown in Table 2.

Table 2 - Optimal angular speed that rotor generates

Wind speed [m/s]	Angular Speed [rad/s]
6	222
7	259
8	296
10	370
12	444
14	519
16	593

Wall motion of the wind turbine blades, describes a rotational motion relative to adjacent cell zones. Hence, unit vectors and origin of the rotation axis were described again. The wall boundary condition for the rotor had a zero relative speed with respect to adjacent cells. Relatively, to the boundaries conditions of the wind turbine model, no slip condition accounting for wall velocities were imposed.

Relatively to, the solutions methods in the pressure-velocity coupling SIMPLE scheme was used. Spatial discretization methods used are presented in Table 3. Regarding of solutions controls, the default values were used.

Table 3 - Methods applied in spatial discretization solutions

Spatial discretization	
Gradient	Least Squares Cell Based
Pressure	Standard
Momentum	Second order upwind
Turbulent kinetic energy	Second order upwind
Specific dissipation rate	Second order upwind

The convergence criteria used for continuity was a absolute criteria of  $10^{-4}$ . Based on CFD theory, and according with (Moshfeghi *et al.*, 2012) this range is not sufficient, but for HAWT cases, a better convergence is notoriously very hard to achieve.

## RESULTS

### Experimental

Experimental measurements were performed in wind tunnel, in order to evaluate the electric performance of a wind turbine scaled model. In short, electric power values were obtained at different values of prevailing wind.

Following power coefficient theory an aerodynamic performance of wind turbine operation can be performed. Thus, a study of extracted power by the turbine needs to be evaluated. Therefore, Figure 6 summarizes the average results obtained in wind tunnel measurements of extracted electric power by the wind turbine.

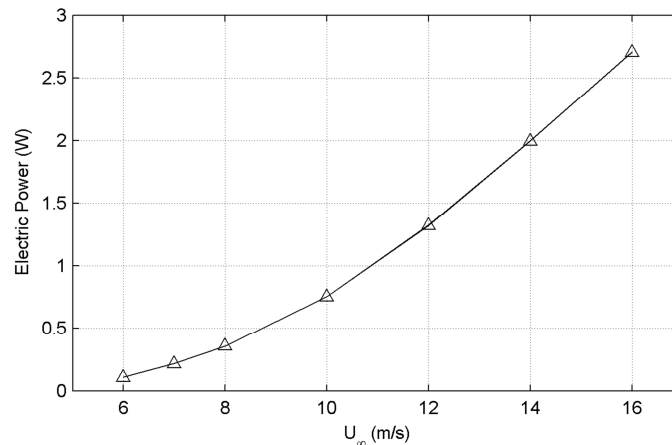


Fig. 6 - Experimental electric power generated by the aerodynamic model in wind tunnel experiments

According to Ribeiro *et al.* (2013) due to inertia of the generator that aerodynamic own model, it's only possible to check production for values exceeding 5.68 m/s. Taking that into account the extracted electric power was evaluated for an initial wind speed of 6 m/s. Figure 6 presents the electric power generated from wind speed of 6 to 16 m/s. These new data allow to make a more comprehensive study, and it's given a larger resolution in the zone where lower wind speeds values are presented.

Power coefficient study shows a somewhat important on description of power performance of wind turbines. Furthermore, regarding to values obtained in wind tunnels tests in Figure 7, corresponding values of power coefficient, are presented.

Performance of the wind turbine was evaluated in terms of the relation between power coefficient with wind speed values, describing a performance curve. According to performance curve shown in Figure 7 a maximum power coefficient at approximately 12 m/s is obtained.

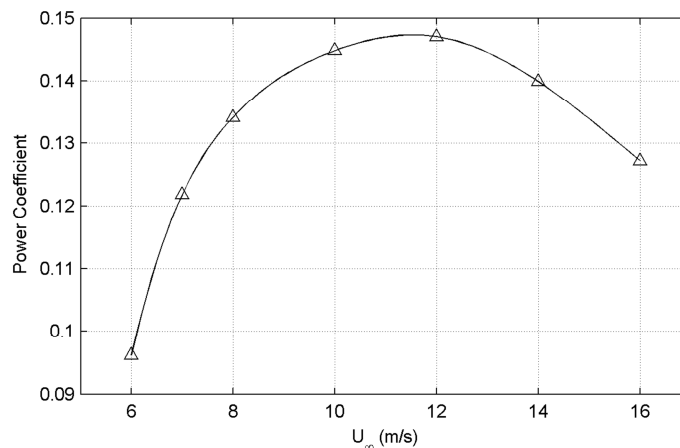


Fig. 7 - Wind turbine power coefficient performance as function of different wind speed values



In order to investigate the energy performance of adapted wind turbine with a concentrator - diffuser, experimental tests in wind tunnel were done. As intend to conduct a confrontation of the energy performance of the two analysed situations the same wind speeds conditions were replicated. As in the previous situation, the electric power produced was evaluated with the aim to determine the coefficient of performance.

Experimental trials make it possible to describe a complete behavior of the electric power produced by wind turbine combined with C-D device. In this case, a significant growth continues to be described in electric power values. Moreover, it's becoming clear that the behavior that C-D induces in electric power production of wind turbine is the enhancement of productivity. Thus, a comparison of electric power generation in both conditions studied becomes notorious an improvement behavior. Therefore, this comparison is described in Figure 8.

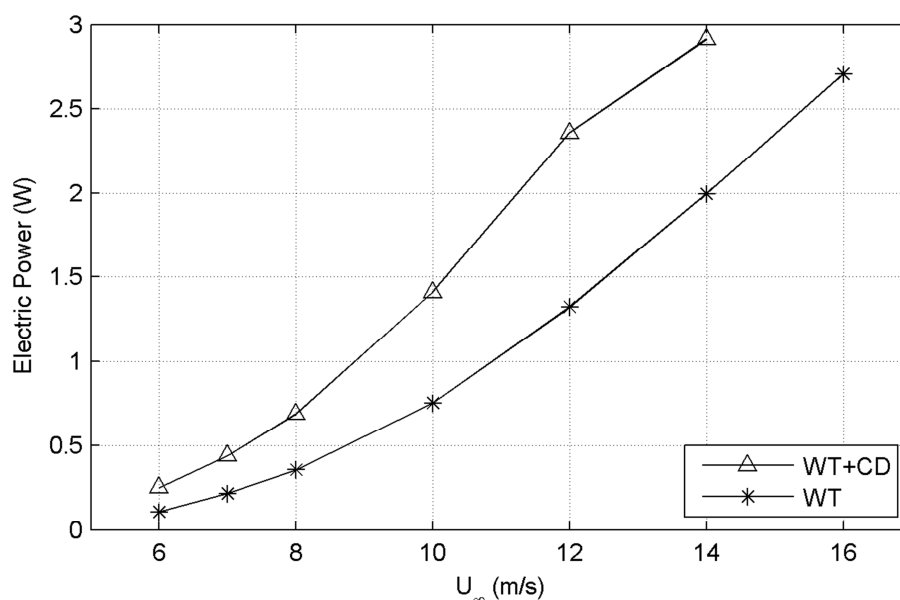


Fig. 8 - Electric power values in function of wind speed, in the case of wind turbine and wind turbine adapted with a convergent-diffuser

The main objective of C-D association is to generate significant improvements in production output. As can be seen from Figure 8, this goal was achieved. In fact, adaptation of C-D can produce an enhancement in electric power, caused by the concentration and acceleration of air flow that surrounding wind turbine. C-D application can effectively produce increments in air flow acceleration conclude in a somewhat enhancement in power output. Table 4 can support the increment that implementation of C-D produces in production of wind turbine.

It's worth noticing, as shown in Table 4, C-D device produces in wind tunnel experiments a maximum increase of 127 % and an average increase of 89 %. Therefore, laboratory measurements shown that is possible to attain increases in power output by a factor of 1:5 - 2:3 comparatively to a conventional small wind turbine. In short, the implementation of C-D produces improvements in electric power for all wind speeds studied, nevertheless, is more pronounced for lower wind speeds.

As previously stated, power coefficient plays an important role on the evaluation of wind turbine performance. Thus, in Figure 9 are presented the power coefficient performance as function of different wind speed values, of the resultant experiments made to the wind turbine and to the wind turbine combined with concentrator-diffuser.

Table 4 - Comparison of electric power production data in function of wind speed values obtained for both situations

	Wind speed [m/s]						
	6.00	7.00	8.00	10.00	12.00	14.00	16.00
WT (W)	0.11	0.22	0.36	0.75	1.32	1.99	2.71
WT + C - D (W)	0.25	0.44	0.69	1.41	2.36	2.91	-
Variation (%)	127	100	92	88	79	46	-

According to the performance curve presented in Figure 9, a performance widely superior is described in the curve of wind turbine combined with C-D relative to wind turbine operation.

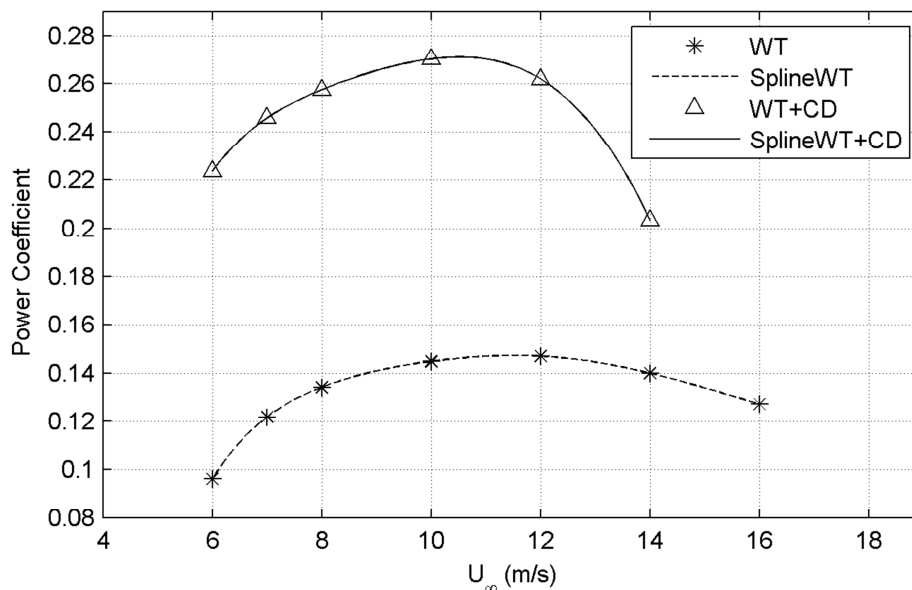


Fig. 9 - Evaluation of power coefficient performance performed to the wind turbine and wind turbine combined with Concentrator-Diffuser in function of wind speed values

Additionally, with C-D implementation a maximum power coefficient is attained at lower wind speeds values, describing at this case a maximum power coefficient at 10 m/s, relatively to a maximum power coefficient achieved at 12 m/s. for the case of wind turbine operation. These results help to highlight, that with the C-D implementation is possible to extract a maximum power coefficient on the wind turbine production considering lower values of approaching wind.

Furthermore, C-D implementation induces increments in power coefficient performance for all of the wind speeds values experienced. In spite of this, is verified that for lower wind speed values a higher power coefficient value is achieved relative to higher wind speed values. Therefore, these considerations help to evidence that C-D implementation in small wind turbine enhance the wind turbine performance comparative to a conventional small wind turbine. Additionally, at lower wind speed values a higher improvement at wind turbine performance is verified. Furthermore, the Table 5 it's possible to verify the coherence of these affirmations.

Values presented in Table 5 describe an enhancement of the wind turbine performance, more pronounced at lower wind speed values. Moreover, Table 5, shown a maximum increase of 120 % and an average increase of 90 %. In addition, convergent-divergent adaptation produces power coefficient augmentation by a maximum factor of 2:2 relatives to the rotor without the C-D structure.

Table 5 - Comparison of power coefficient data in function of wind speed values obtained for both situations

	Wind speed [m/s]						
	6.00	7.00	8.00	10.00	12.00	14.00	16.00
WT (W)	0.10	0.12	0.13	0.14	0.15	0.14	0.13
WT + C - D (W)	0.22	0.25	0.26	0.27	0.26	0.20	-
Variation (%)	120	108	100	93	73	43	-

Thus, following the high potential for exploration that urban environment presents small wind turbines associated with C-D devices can become effectively part of the solution for production of electric energy.

## Numerical

In attempt to evaluate the wind turbine performance through computational tools, CFD calculations were implemented.

Calculations were performed with the main objective of extract the numeric torque that wind turbine generates at different wind speed values.

One relation between computational time spent and mesh quality was considered. In spite of this, the simulations were performed with a coarse mesh that in other words translates to a mesh with a reduced number of elements.

Figure 10 shows the power coefficient performance relative to the experimental power coefficient curve.

Through Figure 10 it can be stated that the behavior of experimental and numerical data described are not similar. It also can be stated that, numerical curve does not show the usual bell-shape form that, for example experimental curve presents.

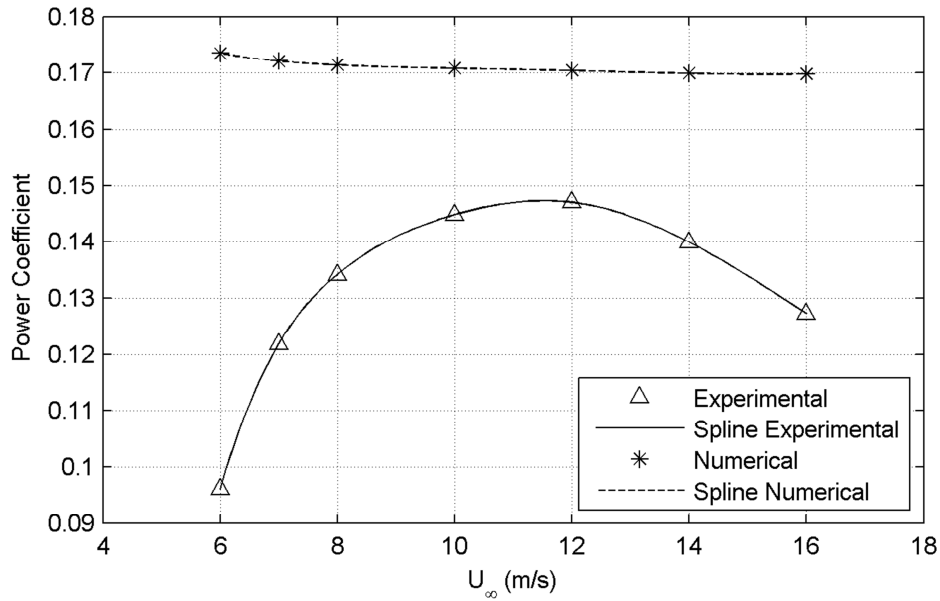


Fig. 10 - Power coefficient confrontation through experimental and numerical data in function wind speed values

Although the magnitude of the values meets up considerably next to the values obtained experimentally, it can be stated that the numerical methodology applied was not satisfactory due to the fact that was not possible to obtain a performance curve close to the ones obtained experimentally.

Nevertheless, CFD calculations were performed to the fluid flow that surrounding the C-D device. Further, for flow velocity equal to 6 and 14 m/s were studied.

In Figure 11 is described the effects that C-D implementation produces in the surrounding air flow, in regarding of 6 and 14 m/s, respectively.

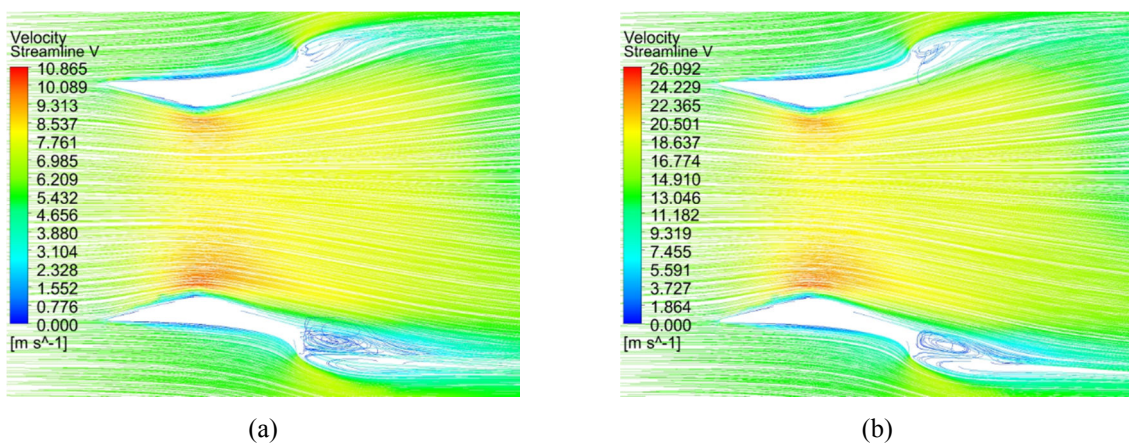


Fig. 11 - Computational mesh generated for the analysis of rotor performance

As presented in Figure 11, C-D generates a somewhat higher velocity values in the zone where the wind turbine rotates.

Also, with a careful analysis is verified that in the C-D output are generated smaller vortices that reduce the air flow velocity. Further, this turbulence generated can affect the suction effect that enhances the mass-flow. The vortices generated do not produce significant differences with the air flow velocity increase.

As C-D exploits the Venturi effect, streamlines shown in Figure 11 are produced to ensure that the reduction of concentrator diameter generates higher velocity values in the wind turbine active zone.

Moreover, C-D device produces at a wind of 6 m/s a maximum percentage increase of 81 % and an average increase of 55 %. Relative to the case of 14 m/s one maximum increase of 86 % and an average increase of 60 % are described

## **CONCLUSION**

In this work, were performed experimental and numerical simulations to an aerodynamic model of a small wind turbine adapted with a Concentrator-Diffuser (CD). It was evaluated the improvement that this device generates in wind turbine electric production, in terms of power coefficient performance.

Experimental study was performed in a subsonic wind tunnel and at values of approaching wind ranging of 6 to 14 m/s. With regards to numerical simulations, ANSYS FLUENT was used and chosen to reproduce the rotor performance and confrontation attempted between the generated values from experimental data.

Laboratory measurements on the wind turbine power performance were attained an augmentation on the power production, by a factor of 1:5 - 2:3 comparatively to a conventional small wind turbine. These factor obtained in this work, comparatively to previous studies made for distinct shrouds design, are in the same order of magnitude, presenting in some cases and enhancement more pronounced.

In terms of power coefficient performance, a maximum increase of 120 % and an average improvement of 90 % were obtained. This augmentation is more noticeable at lower wind speed values, therefore, the adaptation of one small wind turbine with a concentrator-diffuser turns to be an important synergy. In addition, improvements in power production at zones described by low cut-in speeds can be achieved, offering such benefits for one plausible implementation in urban environments.

Relatively to numerical simulations, preliminary results were obtained. Preliminary data describes a non-particular similarity with those obtained in experimental tests, were a non-bell-shaped curve was obtained in the performance of power coefficient. In spite of this, was obtained numerical power coefficient values somewhat superior to those relative to experimental trials. Therefore, improvements in numerical methodology must be applied to reproduce correctly the performance curve described in experimental tests. Moreover, due to these factors, numerical simulations to ensure the wind turbine performance adapting a C-D were not performed. Despite of this, CFD calculations were performed at surrounding air

values of 6 m/s and 14 m/s to C-D device. C-D design, at these air flow velocities concluded in a maximum percentage increase of 81 % and an average increase of 55 %. Relative to the case of 14 m/s one maximum increase of 86 % and an average increase of 60 % were attained.

Efforts in improving the aerodynamic performance of small wind turbines should be encouraged, since the best practices must be implemented in the enhancement of the electrical performance of small wind turbines.

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