Journal of Urban and Environmental Engineering, v.12, n.1, p.147-153

ISSN 1982-3932
doi: 10.4090/juee.2018.v12n1.147153

Journal of Urban and Environmental Engineering

www.journal-uee.org

EXPERIMENTAL STUDY OF THREE DIFFERENT AIRFOILS APPLIED TO DIFFUSER-AUGMENTED WIND TURBINES

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Received 5 October 2017; received in revised form 1 August 2018; accepted 8 August 2018

Abstract: Over the years the electricity generation based on alternative energy systems applied to remote regions has been increased in Brazil, mainly due to the lack of conventional electric grid structure, specially in places as the Amazon. In this scenario, it is well-known that the wind power technology attracts great attention because the wind potential available in the country coast is really representative, leading this sort of technology to an important position into the local energy matrix. However, it is necessary to search new technology developments in order to get efficient turbines applied to isolated regions, where usually low wind speeds are found. The small wind systems using diffuser appear as a relevant alternative, which can be adapted to the characteristics of low wind speed conditions. Hence, in this work, an experimental study on diffusers using three different airfoils (SELIG 1223, EPPLER 423 and NACA 4412) was performed. The goal was to evaluate the influence of the diffuser velocity ratio on the classical theory (axial moment theory with diffuser), in order to show the increasing efficiency typically noticed in studies on Diffuser-Augmented Wind Turbines (DAWTs). In this regard, it was concluded that the wind speed increases under diffuser effect even whether the geometric model is composed by two straight parallel airfoils. Consequently, a DAWT might be adapted to low wind speeds usually found in northern Brazil.

Keywords: Wind turbine; diffusers; renewable energy

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INTRODUCTION

The development of new technologies for renewable energy has been stimulated in Brazil. Such behavior is due to environmental impacts caused by two main sources used for power generation in the country: (a) fossil fuels that drive combustion engines coupled to generators, and (b) water, which generates energy through large hydroelectric plants (Barbosa *et al.et al.*, 2005). In the Amazon region, for example, many communities still suffer the lack of electricity, due to the distances from the power transmission electric grid already installed, and the low consumer demand for the high investments required. The rise of the Brazilian industry has resulted in a significant growth in energy consumption, showing that is necessary more investment in alternative energy sources, especially renewable ones. These facts show the necessity to develop low cost technologies for handling small and medium energy demands in isolated regions (Wiener & Koontz, 2010).

Wind energy is usually obtained through the use of wind turbines. These kind of equipments are machines that extract energy from the wind by aerodynamic effects acting on the wind rotor (Vaz *et al.et al.*, 2018). The blades of modern wind turbines use specially airfoils developed to be equivalent to those used in aircraft wings. Besides what, the lift and drag coefficients vary according to the angle of attack and Reynolds number. These airfoils are setup having different dimensions and angles over the blades in order to provide the best aerodynamic efficiency (Rio Vaz *et al.et al.*, 2018; Tenguria *et al.et al.*, 2011; Hansen, 2008).

In places with low wind speeds, DAWTs may be very useful and effective alternative for electricity generation. Since the diffusers are devices installed around turbine, aiming to increase the flow velocity through the rotor plane, it may improve the extraction of kinetic energy from the wind (Vaz & Wood, 2018). As the electric power generated is proportional to the cube of the freestream wind velocity, a small increase in the wind velocity causes a significant increase in the generation of electricity, justifying the use of such devices upon conventional turbines (Barbosa *et al.*, 2015).

The use of diffusers in wind turbines is not as widespread as in the industrial environment when compared to traditional turbines. It is because there is a significant additional cost for making the diffuser and the structure that supports it. However, for small turbines such technology has increased in the last few decades, becoming it really interesting and also economically attractive. In Brazil there is a great potential for the use of wind energy, however many of the equipment used in these systems, even though manufactured in Brazil, they still use imported technologies and their aerodynamic characteristics, in general, are not appropriate to the local wind conditions (Silva & Filgueiras, 2003). Pará state is bathing by the Atlantic Ocean to the northeast, and studies conducted by Frade & Pinho (2000) have shown that the wind potential in this region is interesting for wind generation, especially for small systems.

Thus, this work proposes the development and manufacture of aerodynamic diffusers to be used in wind turbines, having as the main goal the experimental measurements of three different diffusers (SELIG 1223, EPPLER 423 and NACA 4412) in order to obtain better results in the design of efficient wind turbines, concluding that the wind velocity increases under diffuser effect even whether the geometric model is composed by two straight parallel airfoils. Consequently, a DAWT can be adapted to low wind velocities usually found in northern Brazil. Additionally, the results show that, theoretically, a DAWT may achieve 74% of efficiency, exceeding the Betz-Joukowsky limit (59.3%).

DIFFUSER-AUGMENTED WIND TURBINES

The study of wind turbines with diffusers, known as DAWTs was started around the 1920s, when the benefits of using diffusers in turbines were discussed for the first time. However, the application of diffusers and existing models at the time made the use of this equipment economically unviable. Most work available in the literature has examined a parameter named speed-up factor, or simply speed ratio (Silva *et al.*, 2018; Vaz & Wood, 2016; Rio Vaz *et al.*, 2014). This ratio, in the presence of the turbine, is defined by the ratio between the effective velocity along the turbine and the incident speed. For the case in which the flow is evaluated only around diffuser, the speed ratio is defined as the ratio between the flow velocity on the axial direction of an effective reference plane and the incident freestream velocity.

Betz (1929) recognized the potential of wind turbines with diffusers and was the first to develop a theory for DAWTs where assumed that the static pressure at the diffuser exit plane would be equal to the ambient pressure. Another restriction imposed by its theory was that the ratio between the diffuser exit area and the area of the rotor plane, called area ratio, should be small, leading to small speed ratios. From these findings, the idea of using diffusers in turbines was abandoned until 1950, when Sanuki (1950) published experimental results of a DAWT indicating a power increase of 88% over the Betz-Joukowsky limit. As further described by Barbosa *et al.* (2015), the increase in power of a wind turbine results from two main mechanisms: increasing the mass flow and turbulent flow with external mixing. To improve the efficiency of a DAWT, some concepts have been used alone or in combination, such as: vortex generator, cylindrical obstruction and creating diffuser effect, as also reported by Phillips (2003).

Regardless of the authors who have studied the power gain in wind turbines, everyone agrees that this increase in efficiency is achieved with rotors 'channeled' or 'pipelined'. Such gain is done by means of two effects: (a) reduction in blade tip losses and (b) an increase in the axial velocity of the rotor obtained by the control of the turbulent wake, as stated by Lilley & Rainbird (1957). They also have indicated that a DAWT can produce twice as much power as compared turbine without diffuser with the same rotor diameter. They also suggest that the presence of a flap (similar to the element used in aircraft to control aerodynamic lift of the wings) in the diffuser exit plane would minimize the problem of flow separation which occurs due to the increase of the opening angle of the diffuser.

Nowadays, the diffuser technology has still been source of research worldwide. For example, Vaz & Wood (2016) reported that the addition of an exit diffuser to a horizontal-axis wind turbine is one of the few ways in which power output may be increased. In their work, a new approach to the aerodynamic optimization of a wind turbine with a diffuser was proposed, which was based on an extension of the well-known Blade Element Theory (BET) and a simple model for diffuser efficiency.

EXPERIMENTAL SETUP

In order to perform an evaluation of airflow along aerodynamic diffusers with rectangular section without turbine, three diffusers with distinct geometric dimensions and adjustable angles of attack have been used to evaluate the distribution of velocities within each diffuser, as well as comparing the speed distributions in each one.

The equipment, instruments and materials used in the measurements were: wind tunnel, Pitot tube, micromanometer and soft wood. The wind tunnel is a facility that aims to simulate the effect of airflow over or around solid bodies. The airflow speed in the wind tunnel is controlled by a frequency inverter, which varies the fan rotation that moves the air. The wind tunnel cross section used in this work was of 300 x 300 mm². The Pitot tube was the probe which provided the flow velocity from measurements of the static and stagnation pressures. The difference between these two pressures is called dynamic pressure. The pitot tube used in this study was the L-type with 5 holes having a diameter of 7 mm, length of 310 mm and error laid down in ± 2%. Digital micromanometer is a device designed to measure small differences in pressure. It operates according to the principle of piezoelectricity, measuring pressure by means of a voltage generated in a piezoelectric crystal. The micromanometer operating range used here was of 0-18 m/s, with an uncertainty of 0.25% reading indicated for speed measurement and acquisition rate of 4 Hz. Soft wood was the material used in the construction of airfoils and diffusers used in the experiments. **Figure 1** shows the diffuser construction and assembly.

Selection of the measuring points

For the tests, it was necessary to adopt a distribution point velocity measurement through each diffuser. In order to provide standardized measurements, it has been used a spacing of 150 mm from the exit of the wind tunnel, and a spacing of 15 mm between each acquisition point on the diffuser (**Fig. 2**). These points were also repeated for all diffusers.

Mapping airflow at the wind tunnel exit

Wind velocity measurements were performed with the diffusers positioned externally to the wind tunnel test section, due to its cross section (300 mm x 300 mm) be small, being susceptible to the blockage effect on the flow. Thus, it was necessary to map the region of influence of this flow to verify whether it would remain uniform as the diffusers moved away from the exit of the wind tunnel. For this purpose, three velocity profiles were measured along the axial direction, from the wind tunnel exit without presence of diffuser, with a spacing of 150 mm between each profile, and a total distance of 450 mm, as shown in **Fig. 3**.

Fig. 1 Design of the airfoil and alignment for assembling the diffuser.

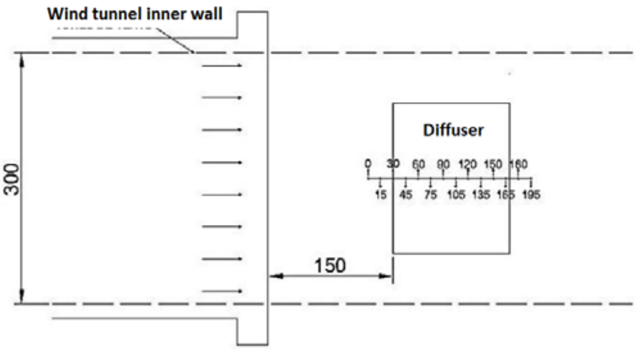


Fig. 2 Distance between the diffuser and the wind tunnel exit.

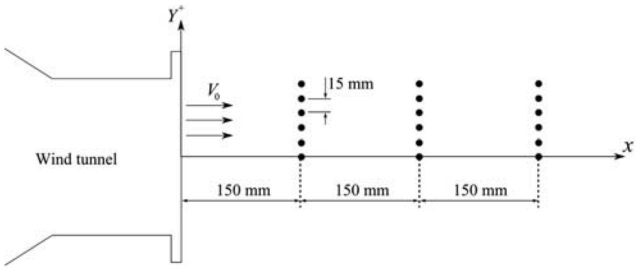


Fig. 3 Measuring points for the velocity profiles outside wind tunnel.

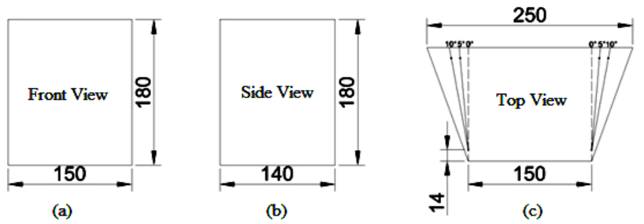


Fig. 4 Diffuser dimensions.

Diffusers dimensions and airfoils

The diffusers used in this experiment were built in reduced scale due to the geometric constraints of the wind tunnel. Their dimensions (all in millimeters) are depicted in **Fig. 4**.

The variation of the angle of attack in each profile was of 0°, 5° and 10°. This variation aimed to find out an angle to the diffuser that offers a higher flow rate during the test. For this work, three diffusers with the same dimensions and rectangular section were used. The only difference was on the airfoils chosen, shown in **Fig. 5**.

RESULTS AND DISCUSSION

In this section, the results are shown and discussed. First, as the diffusers were positioned at the wind tunnel outlet, it was necessary to map the behavior of the velocity profile in order to assure the correct condition to make the measurements. Second, the influence of the diffuser effect on the classical theory has been made.

Velocity measurements along the diffusers

Regarding the measurements, each diffuser was kept to 150 mm away from the wind tunnel outlet. A support to maintain the diffusers at the desired position (**Fig. 6**) was rigid enough to minimize vibration (transverse displacement) when the wind tunnel was in operation. The diffusers had their axes aligned with the longitudinal axis of the wind tunnel, keeping the air flow parallel to the axis as much as possible. Incident velocities upstream, inside and downstream of the diffuser were evaluated in this experiment. The displacement on the longitudinal direction of the pitot probe was made manually through small orifices equally spaced, resistant sufficiently to bear the effects of the fluid flow, aiming a satisfactory data acquisition to the experiment.

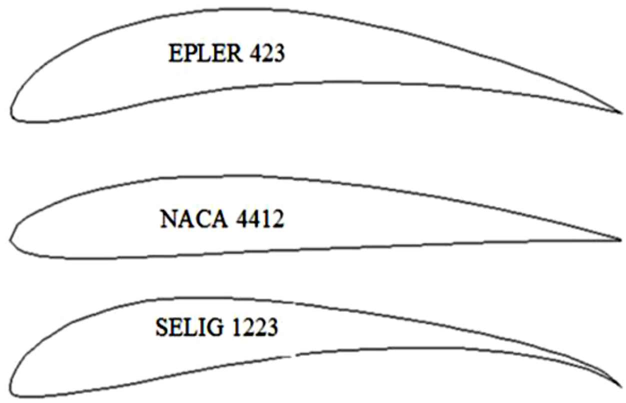


Fig. 5 Airfoils used in the diffusers.

For each diffuser, the speed measurements were initiated upstream of the diffuser through the internal region, terminating downstream of the diffuser. The pitot probe has been moved in the longitudinal direction to the next measuring point. At each time was necessary to move the pitot probe within the diffuser. The speed readings made by micromanometer were performed on samples of 250 measurements at a rate acquisition of 4 Hz and sent directly to the microcomputer. At each point a wind tunnel speed of 6.0 m/s was used. This value was taken because it was an intermediate between 4.05 and 9.05 m/s, which were the values used in the sensitivity analysis. This speed (6 m/s) was also set because it is compatible to low wind velocities incidents in the coastal regions of northern Brazil, as described in Blasques *et al.* (2010). The total acquisition time for the speed measurements was approximately 25 hours.
The results show the velocity distribution along the y-axis away 150, 300 and 450 mm from the exit of the wind tunnel set to 4 and 9 m/s. **Figure 7** shows the velocity profiles plotted simultaneously, so as to

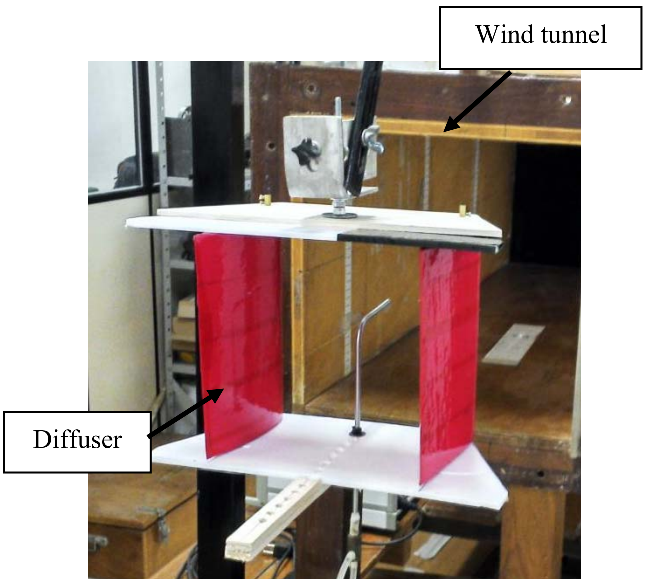
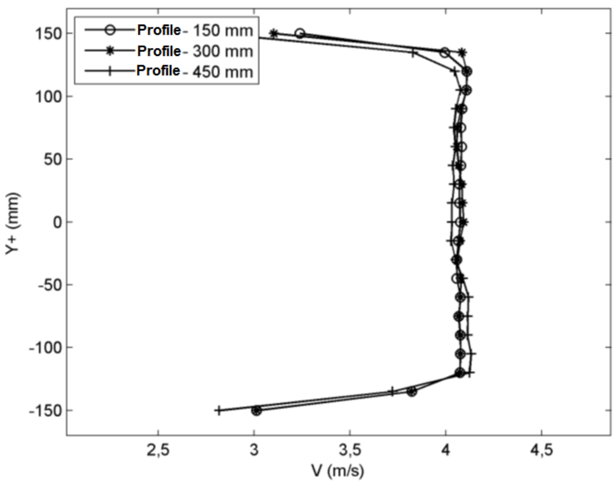


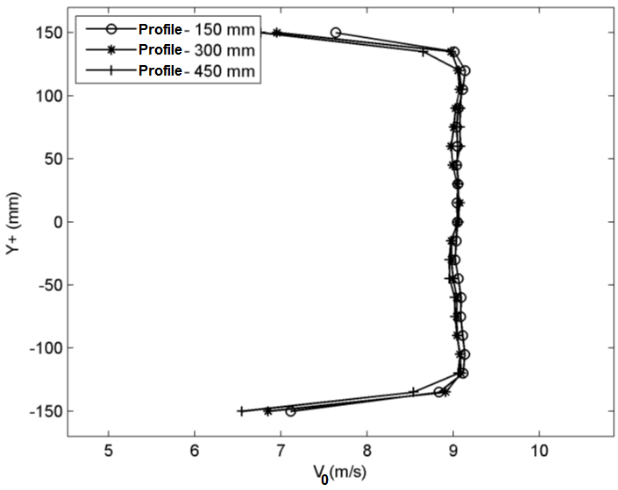
Fig. 6 Diffuser positioned at the wind tunnel exit.

compare the measured velocities and the region in which they were uniforms. These results have shown a uniformity of 250 mm vertically, where the flow velocity remained constant so that this flow configuration became satisfactory for the purpose of this work.

The velocity profiles are presented in **Fig. 8** where the x-axis was maintained according to the actual distances in the axial direction and the y-axis contains the values of the velocity ratio. The vertical lines were positioned at x (mm) = 30 (left) and x (mm) = 165 (right), and represent the inlet and outlet plans of the diffuser, respectively. **Figure 8** shows the result for each diffuser, using an average wind speed of 6 m/s. The color lines indicate curves obtained using quadratic polynomial fit with maximum norm of the residuals of 0.0847. The velocity values for each point along the longitudinal axis of the diffusers were made from a sample of 250 measurements as well. The results presented uncertainty of 0.05m/s at 95% of confidence level, which enabled suitable repeatability.



(a)



(b)

Fig. 7 Wind profile outside the wind tunnel in the three points measured for (a) V0 = 4 m/s and (b) V0 = 9 m/s.

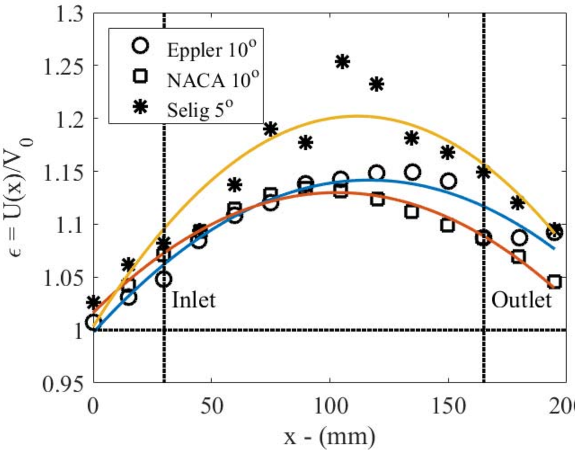


Fig. 8 Comparing the velocity ratio results of the diffusers for V0 = 6m/s.

The horizontal line represents the absence of diffuser, showing that any point above this line indicates an increase in speed as well as points below this line obviously represent reduction in the freestream wind velocity. The three diffusers have shown an increase in velocity. The Reynolds number in all cases was of 71,000.

The diffuser built with NACA 4412 (Abbott & Von Doenhoff, 1959) airfoil and angle of 10 degrees, showed a uniform and well-defined behavior. On the other hand, it was the one with lowest speed ratio (1.13), which resulted in an increase of 13% in velocity.

The diffuser built with EPPLER 423 airfoil at an angle of 10° showed a sharp decline after reaching the maximum speed ratio (1.15), this is likely the boundary layer detachment due to a slightly high angle of attack, which causes disturbance in the flow. Despite these fluctuations, the diffuser showed an intermediary speed ratio, providing 15% increase in speed.

The diffuser built with SELIG 1223 airfoil at 5 ° angle was the best one, increasing speed by 25%. However, it had a behavior with some oscillations, what do not directly interfere in the results. These oscillations are probably due to disturbances at low Reynolds number, which reduces the lift to drag ratio of the airfoil, being quite difficult to be characterized using pitot probe. Additionally, probably the results may be better evaluated by increasing the measurement points and also using precisely equipment. A very good explanation on low Reynolds number is described in Wood (2011).

One important observation is the fact that the flow velocity field in the diffusers vary, because the cross sections of the diffusers were not circular. Thus, the diffuser geometries used here are mostly applied to vertical axis wind turbines.

Diffuser effect on the classical theory

Regarding the actuator-disc theory for vertical axis wind turbines, Newman (1983) has demonstrated that the maximum power coefficient is about 8% higher than for horizontal ones, because the interference of the turbine on the flow velocity field is rather different. Hence, on this issue, the authors are unaware of any study upon actuator-disc theory for vertical turbines under diffuser effect. And then, the simple momentum theory applied to horizontal turbines was taken into account here as an expedient until a better model is developed.

Therefore, according to Vaz & Wood (2016), the simple momentum theory considers the air frictionless and ignores the rotational velocity component. Thus, to evaluate the experimental results obtained in this work on the theoretical power coefficient of a DAWT, the model proposed by Rio Vaz *et al.* (2014) and also used by Barbosa *et al.* (2015) with no losses was considered, which relies on the classical theory for horizontal axis wind turbines (axial moment theory under diffuser effect), given by the **Eq. (1)**.

$$Cp = \varepsilon_{\max} 4a(1-a)^2 \tag{1}$$

where $\varepsilon_{max} = \max[\varepsilon(x)]$ is the maximum diffuser velocity speed-up ratio, and it corresponds to the position where the turbine must be installed in the diffuser. The axial induction factor, a, at the rotor plane can be written as a function of the thrust coefficient, C_T, as shown in **Eq. (2)**.

Table 1. Maximum values for an ideal power coefficient

	Parameters		
	x (mm)	ε_{max}	Cp_{max}
Diffuser 1 (Eppler 10°)	134.80	1.15	0.68
Diffuser 2 (NACA 10°)	89.58	1.13	0.67
Diffuser 3 (Selig 5°)	105.13	1.25	0.74

$$a = \frac{1}{2}\left(1 - \sqrt{1 - C_T}\right) \tag{2}$$

In this case, the interval $0 < C_T < 1$ was considered. Table 1 shows the maximum power coefficient obtained for an ideal wind turbine using **Eqs. 1** and **2**. Note that the maximum diffuser velocity speed-up ratio is the maximum value for each curve shown in **Fig. 8**.

Figure 9 shows the diffuser effect on the power coefficient of an ordinary wind turbine. It is observed that the diffuser improves the efficiency, as shown in Phillips (2003) and Barbosa (2015). In this regard, note that the better results were obtained for the Diffuser 3, which provided 74% of maximum extracted energy, having as a consequence an exceeding produced energy above Betz-Joukowsky limit. Although these results were held for an ideal wind turbine condition, they have a significant impact, through which the diffuser technology appears as an alternative to be implemented in small wind systems, suitable for regions with low wind speed.

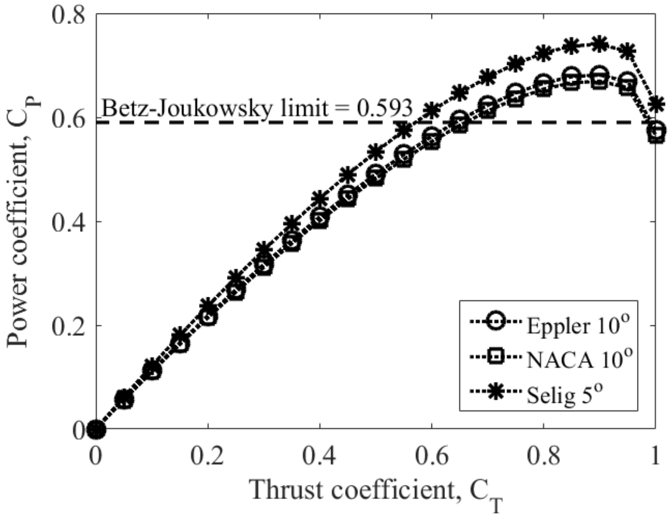


Fig. 9 Power coefficient as a function of the thrust coefficient.

CONCLUSIONS

The main objective of this work was to develop an experimental study of three different airfoils applied to DAWTs, in order to describe the behavior of the airflow within these diffusers. The experimental study presented in this work was of great importance towards to the development of information on airfoil parameters facing the efficient design of wind turbines with diffusers, operating at low wind speeds, especially in locations as existing in Amazon region, where the average speed is around 4-6 m/s (Frade & Pinho, 2000).

Moreover, a significant increase in the rate of airflow was obtained for all diffusers tested here. An especial attention needs to be given for the diffuser constructed with SELIG 1223 airfoil, which provided the best result, enabling a 25% increase in the rate of airflow. The EPPLER 423 airfoil presented an intermediate behavior between the profiles that were tested, with a 15% increase in the rate of airflow. Although the NACA 4412 airfoil have shown stable behavior as the measured velocities, it has presented the lowest speed ratio, about 13% increase in the airflow.

It is necessary to consider some limitations of the present work, such as the impact of area ratio upon DAWT performance, which is still not completely clear, since increasing area ratio typically results in an increasing recirculation zone behind diffuser, leading in general to a decrease in pressure, but this does not lead to more energy extraction by the turbine. Another critical point is the fact that the cross sections of the diffusers were not circular, which clearly might modify the internal velocity field being necessary take into account the radial variation of the flow on the wind rotor.

Acknowledgment The authors would like to thank the UFPA, CNPq, CAPES, and PROPESP/UFPA for financial support. Also, a special thanks to the Fluid Mechanics Laboratory at LABEM/UFPA for technical support.

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