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How to Increase Savonius Power Coefficient: Ducted Rotor Performance with Different Overlap Ratios

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Abstract. The use of ducted configuration to increase the efficiency of wind turbine rotors is gaining wide attention in the scientific community. Specifically for mini and micro rotors in urban environment applications this solution demonstrated to be very attractive. The possibility to overcome the Betz limit for power coefficient was widely demonstrated in ducted horizontal axis wind turbines. However, very few studies have dealt with ducted Savonius rotor despite these rotors represented an efficient solution for urban environment thanks to their simplicity, their cheapness and the low cut in velocity in highly turbulent conditions as well. Furthermore, the ducted Savonius concept, might be applicable to oscillating water column wave energy devices, thanks to its self-rectifying capability and simplicity. For these reasons, the authors carried out an experimental campaign to verify the impact of ducting the Savonius rotor, thus leading the way for a possible exploitation of this configuration in many practical applications. Specifically, The present paper deals with a study of ducted Savonius type air turbine performance. In particular, turbine performance was studied as a function of turbine overlap ratio. Four overlap ratios were tested: 0, 1/6, 1/3 and 1/2. A specific experimental setup was built to test ducted turbine, while bare turbine performance was measured using a wind tunnel. All tests were performed at fixed air velocity: 5 m/s. On the basis of the results, it is possible to state that ducted turbine performance is higher than bare turbine performance, at all tip speed ratios and for all overlap ratios. The optimal turbine overlap ratio is equal of 1/3.

1. Introduction

In order to satisfy worldwide energy demand, in the last century an indiscriminate exploitation of energy sources has been made. As a consequence, pollution and global warming have been increased dramatically. Strategies to slow down and even stop these issues should be considered in worldwide energy policies.

Alternatives to reduce conventional energy sources utilization and its impacts are certainly the introduction of renewable energy in the energy scenario and decentralized power generation as a policy to reduce transportation waste. These strategies will contribute to a sustainable development of societies. Wind energy extraction in urban areas is a very interesting method for energy supply. Moreover, energy generation takes place directly in energy end use site with a decentralization of power generation: the essence of embedded generation.

Nevertheless, its practical implementation at a significant scale presents some problems. Three promising strategies could be identified to drive the introduction of urban wind energy in the market: placement of conventional free-standing wind turbines in an urban environment; retrofitting wind turbines on existing buildings; and integration of wind turbines on specifically designed buildings.

The first issue presents some problems related to large buildings in proximity with low space for freestanding turbines. Safety, noise and vibration issues might present obstacles to growth. Moreover,

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the application of the first strategy needs new construction and suitable turbines. So that the growth of installed capacity could be gradual.
Several progresses have been made with existing buildings retrofitting strategy. Urban wind characteristics (low wind velocity, high turbulence level and aerodynamic noise, etc.) are now being widely studied, and some manufacturers propose building attached turbines [1, 2]. Again, noise, vibration and structural integrity issues arise. In this case concerns over visual impact are important, as well [3, 4]. Some analysts [3] persist to be sceptical of the ability of roof mounted wind turbines to ever make a significant contribution to energy supply. Furthermore, small wind turbines inevitably have higher costs per unit of electricity produced than wind-farm machines, and so are unable at present to compete with conventional sources of energy.
Micro wind turbines could drive the sector. Micro-wind turbines could be classified by the power (less than 2.5 kW) or by the rotor diameter (less than 1.25 m) [5]. From a commercial point of view micro-wind turbines power range is 0.4 kW ÷ 1.5 kW with a wind speed of about 12 m/s [1]. Notwithstanding of their evident potential, wind turbines installation in urban areas has not yet been widely accepted because of low wind speeds and high levels of turbulence in the area, as well as high aerodynamic noise levels generated by the turbines.
Savonius turbine could be suitable for exploiting wind energy in urban areas due to the low wind velocity operation, low installation costs and relatively high efficiency. Aerodynamics noise and vibration still persist.
In order to increase turbine efficiency, building mounted ducted wind turbine could be an interesting method to increase turbine performance in terms of generated power and efficiency [6, 7, 8].
Therefore, in the present paper a study on Savonius turbine performance in ducted configuration for building mounted application is shown. The study was conducted experimentally, and the turbine performance were measured as a function of turbine overlap ratio.

2. Background

Savonius type wind turbine is the simplest vertical axis self-rectifying wind turbine (VAWT). The turbine has half-cylindrical shaped blades attached to the opposite sides of a vertical shaft. Torque is generated by drag forces over the blades. Thus, the turbine cannot rotate faster than the wind speed with a tip speed ratio equal to 1 or smaller [9].
Two different forces are generated on those type of blade surfaces (convex and concave) in the interaction between air flux and turbine rotor (drag and lift forces). The basic principle is based on the difference of the drag force between the convex and the concave parts of the rotor blades when they rotate around a vertical shaft. Therefore, drag is the main driving force of the Savonius rotor [10], so that the Savonius rotor was named “drag wind turbine” by Butaud and Besnard [11]. Analysing the dynamic of the Savonius rotor operation it is evident the influence of the lift force [11]. Hence, a specific classification could not be done for Savonius turbine. The dynamic analysis highlights that the efficiency at starting of this turbine is mainly due to drag force, but its maintenance in rotation is mainly due to the lift force [11].
Figure 1 shows main characteristic parameters of a Savonius wind turbine with two semi-circular profile blades. All these parameters affect turbine performance.

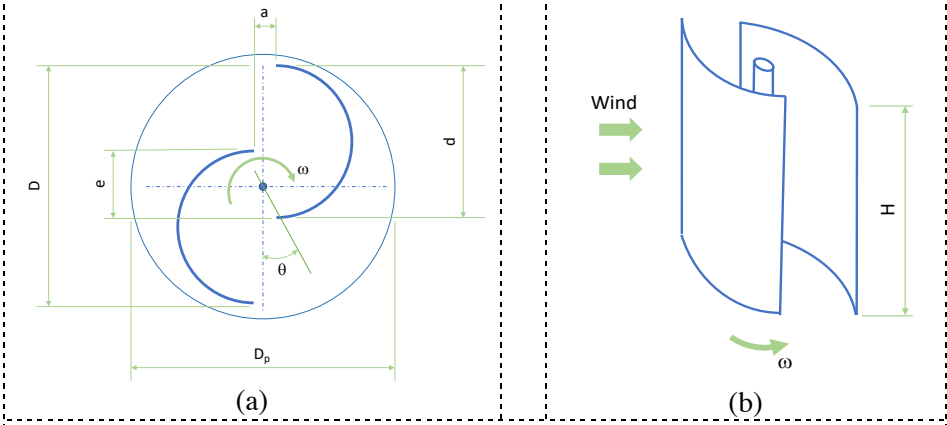

Figure 1. Principal characteristic parameters of a Savonius wind turbine with two semi-circular profile blades.

Referring to Figure 1, a conventional Savonius turbine has a rotor with the geometrical parameters "a" and "e" respectively equal to 0 and D/6. This rotor has been largely studied [12], and the values of the turbine coefficient of power (C_p) and torque coefficient (C_T) are experimentally determined as a function of the tip speed ratio (λ).
The main geometric parameters that affect Savonius turbine performance are:

1. Number of buckets (N_b)
2. Aspect Ratio "H/D"
3. Overlap Ratio "e/D"
4. Spacing Ratio "a/D"
5. End plates presence

Considering a bare Savonius turbine in free stream, the turbine performance is strongly affected by the rotor's number of buckets [13, 14, 15]. According to Saha and Thotla [13], the optimum Savonius turbine number of blades is 2. Saha and Thotla [14] studied single, two and three stage turbines coming to the same conclusion. Hadi Ali [15] comes to the same conclusions of Saha and Thotla [13, 14] obtaining highest power coefficient with a Savonius turbine with only two blades.
As far as the turbine aspect ratio H/D is concerned, this geometric parameter influences the aerodynamic performance of Savonius rotors as highlighted by Mahmoud [15] that tested Savonius turbine with different aspect ratios coming to the conclusion that higher the turbine aspect ratio higher the turbine power coefficient. Different design of Savonius rotors leads to low aspect ratios with better performance [12, 16, 17]. With new design better turbine performance is registered using an aspect ratio in the range 1.5 – 2 [17].
The structure of the flow within the rotor is strongly dominated by the turbine overlap ratio. Thus, this parameter influences the aerodynamics of the rotor blades and at the end the turbine performance. Different studies were carried out in this topic. Considering the optimum value of a bare Savonius turbine overlap ratio that leads to best turbine performance, Blackwell et al. [18] state that the optimum OR is in the range 0.1 to 0.15, while Menet [19] extends this range up to 0.3 indicating the best OR in 0.245. According to Akwa [20], the configuration of Savonius rotor that has the best rotor performance is the one with an OR equal to 0.15.
The effects of turbine buckets spacing were studied by several authors [20, 21, 22]. These studies conclude that the best Savonius performance were achieved using a null bucket spacing. This result is due to a satisfactory focus of the air on the concave portion of the returning bucket that maximize turbine power.
The performances of Savonius turbine are influenced by the presence of the end plates. These are simple plates at both rotor ends, able to increase turbine performance. The presence of end plates increases the

turbine power coefficient (an average increase of about 30% was measured [20]), while the tip speed ratio at which maximum c_p occurs moves to higher value ($TSR_{Cp\text{-}max}$ is doubled [21]).
Turbine end plates effects on turbine performance are related to the fact that end plates presence avoids air escaping from turbine active buckets, while maintaining at optimal level pressure difference between buckets convex and concave sides.
According to the scientific literature about the optimal size of the turbine end plates, it is unanimous that turbine end plates should have a negligible thickness compared to the turbine height, while their diameters should be 1.1 times the turbine rotor diameter [11, 20, 21, 22, 23, 24].

3. Materials and Methods

In order to test turbine performance in bare and ducted configurations, two different experimental setups were implemented.
In the present paragraph a brief description of the experimental setups is given, as well as torque measurement method. A description of the tested turbines is given, as well.
A simple band brake was implemented to measure turbine torque. Band brakes can be simple, compact, rugged and can generate high force with light input force. Moreover, band brakes are very effective (require low input force to achieve high brake force) and give the possibility to have a very fine control on the generated brake torque.
The brake is used to apply the load to the turbine shaft, controlling the turbine rotational speed at its operating condition, as well as to measure turbine torque. Figure 2 shows a schema of the proposed brake.
The band brake consists of the following components:

1. a pulley
2. a nylon-coated metal wire
3. a suspended mass
4. a load cell

Referring to Figure 2(a), the turbine rotor and its shaft are supported by two bearings and are rotationally free. The pulley is joined to the turbine shaft and rotates in solidarity with turbine rotor. A nylon-coated metal wire is joined to a load cell fixed to the ground, it passes over the pulley and suspends a mass at the other end. Varying the suspended mass, it is possible to regulate turbine load (with a brake torque) and control its rotational speed. By measuring forces with the load cell and turbine rotational speed, it is possible to calculate turbine torque and power. In Figure 2(b), a dynamic forces balance is shown. In the Figure 2(b), F_1 represents the weight force of the mass m, while F_m is the force measured by the load cell and F_f is the friction force over the pulley. In static condition F_m is equal to F_1, while in dynamic condition F_m is equal to the sum of F_1 and F_f. Therefore, it is possible to evaluate friction force F_f and then turbine torque using pulley radius R_p. Main brake characteristics are reported in Table 1.

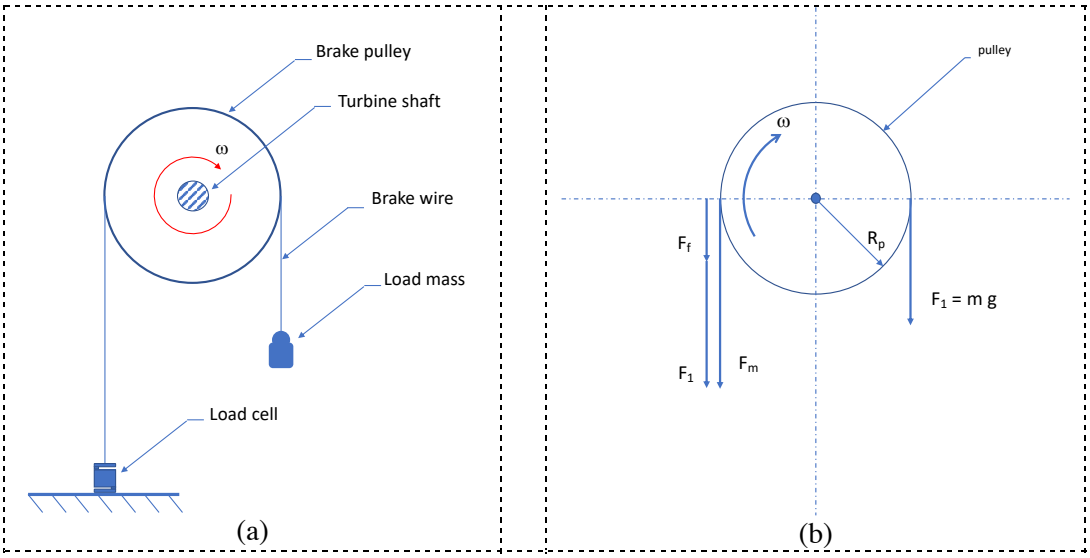

Figure 2. Schema of the implemented band brake.

Table 1. Main band brake characteristics.

Parameter	Description
Brake pulley	Radius 11 mm Material Aluminium
Load Mass	Mass 0 – 10 g
Brake Wire	Nylon-coated metal
Load cell	± 5 N

As far as the bare turbine tests are concerned, they were carried out by means of a wind tunnel. The latter is a closed loop wind tunnel with the testing section of 500x500x1200 mm. Air velocity in the testing section can vary in the range 0 to 30 m/s with a turbulence level of 0.4% [26]. In Figure 3 a schema of the testing setup for bare turbines is shown.

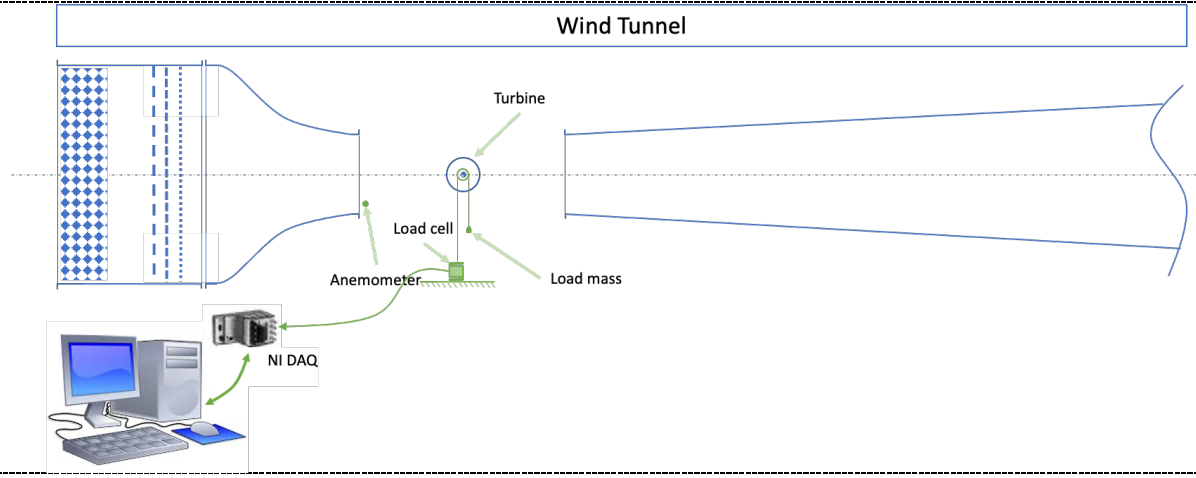

Figure 3. Bare turbine experimental setup schema.

In order to measure ducted air turbine performance, a specific experimental setup was built. It consists essentially of a prismatic air tube (testing tube) in which turbine runs. The testing tube is 100 mm high, 100 mm wide, 1000 mm length and it is made of transparent materials to allow Particle Image Velocimetry (PIV) measurements [26]. An air generator blows air with an imposed velocity into the testing tube. Figure 4 shows a schema and a photograph of the implemented experimental setup. The experimental setup was designed to have the possibility of an alternated flow into the testing tube for future oscillating flow tests (Oscillating water column wave energy converters). In the present work it was maintained monodirectional.

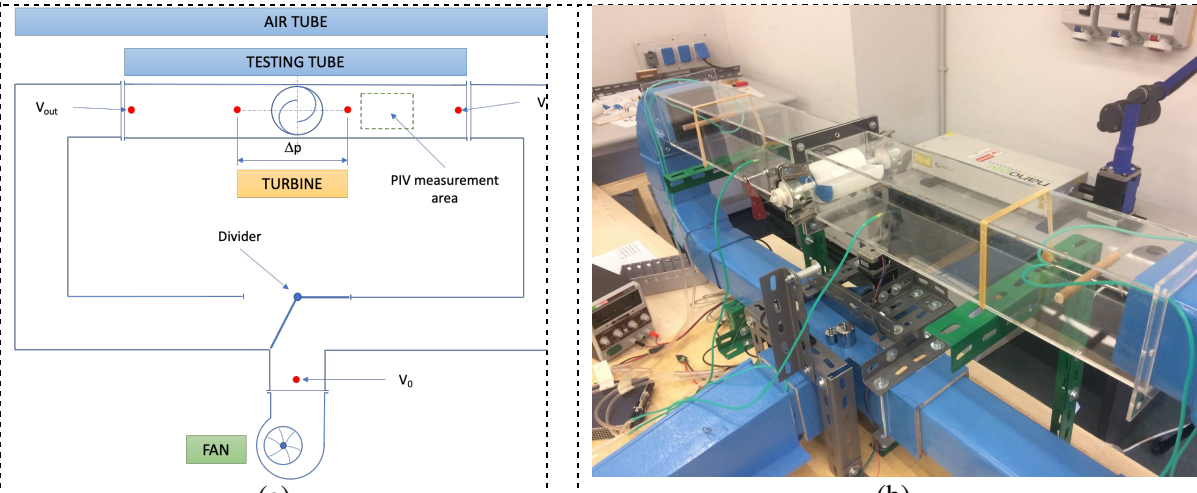

Figure 4. Ducted turbine experimental setup: (a) schema, (b) photograph.

The fan (see Figure 4(a)) blows air into the air tube and a divider could deflects air flow in one direction or in another. In the present work a counterclockwise flow was imposed. The air velocity can be controlled varying fan rotational speed. With reference to Figure 4(a), the velocities at the air tube entrance (V_0) and at testing tube end (V_{in}) were measured using pitot tubes. In the same manner, static pressure drop across turbine (Δp) was measured using static pressure sensors at the distance of one dimeter from the turbine.
Four turbines with four different overlap ratios were tested in the present study. In Table 2 rotor main dimensions are reported.

Table 2. Tested turbines main dimensions.

	Turbine A	Turbine B	Turbine C	Turbine D
D	90 mm	90 mm	90 mm	90 mm
e/D	0	1/6	1/3	1/2
H/D	1	1	1	1
ϕ	10 mm	10 mm	10 mm	10 mm

All the rotors were built with an additive manufacturing method [27, 28].
To measure turbine performance as a function of turbine overlap ratio, an extensive experimental campaign was carried out using both setups. Four turbines overlap ratios were studied (0, 1/6, 1/3 and 1/2) at fixed imposed air velocity (5 m/s).

4. Results and discussion

The turbine performance was measured using the described experimental setup and the results were compared for both turbine configurations as a function of turbine overlap ratio.
Turbine power and torque, pressure drop across turbine and inlet air velocity were measured and turbine power coefficient as a function of tip speed ratio was determined.
In Figure 5 the power of bare and ducted turbines were compared; in Figure 6(a) a comparison on power of bare turbines is shown, while in Figure 6(b) a comparison on power of ducted turbines is shown.

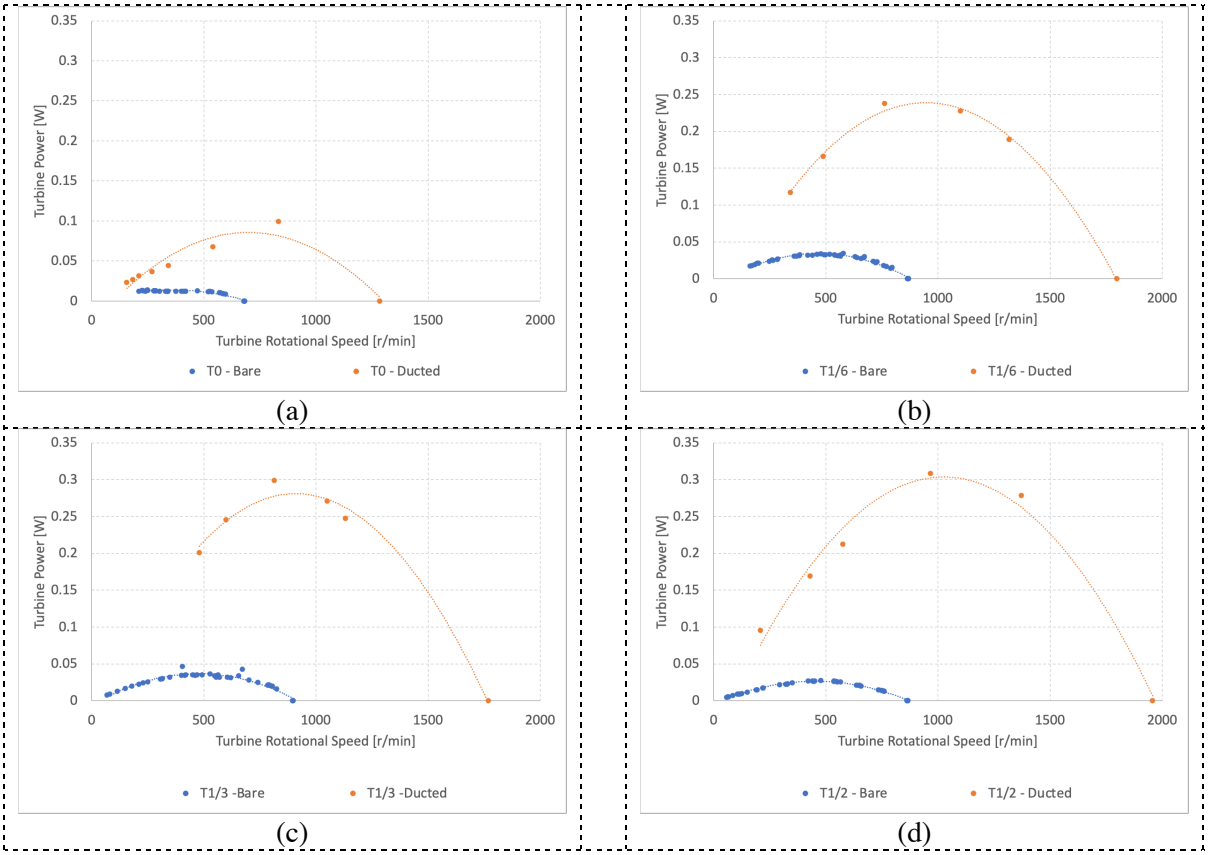

Figure 5. Turbine power for different turbine overlap ratios in both ducted and bare configurations: (a) OR = 0, (b) OR = 1/6, (c) OR = 1/3, (d) OR = 1/2.

As showed in Figure 5, it is evident that ducted turbine power is much higher than bare turbine one. An increase in turbine operating rotational speed range was also registered as well. This behaviour was observed for all studied turbine overlap ratios.
Considering maximum power, ducted turbine generates about ten times the power generated by the bare turbine for almost all overlap ratios.
This is probably due to two main factors: in ducted configuration the air flow is bound to the duct and crosses through the turbine increasing the power; in addition to the kinetic energy contribution upstream of the turbine, a manometric energy contribution induced by the turbine itself is also available. The increased power allows the higher turbine rotational speed range.
It is evident that both bare and ducted turbine power presents some sensitivity to overlap ratio (see Figure 6).
As it is possible to observe in Figure 6(a), the highest power is generated by 1/3 overlap ratio bare turbine, while, for ducted configuration, 1/2 overlap ratio turbine shows the best performance (see Figure 6(b)).

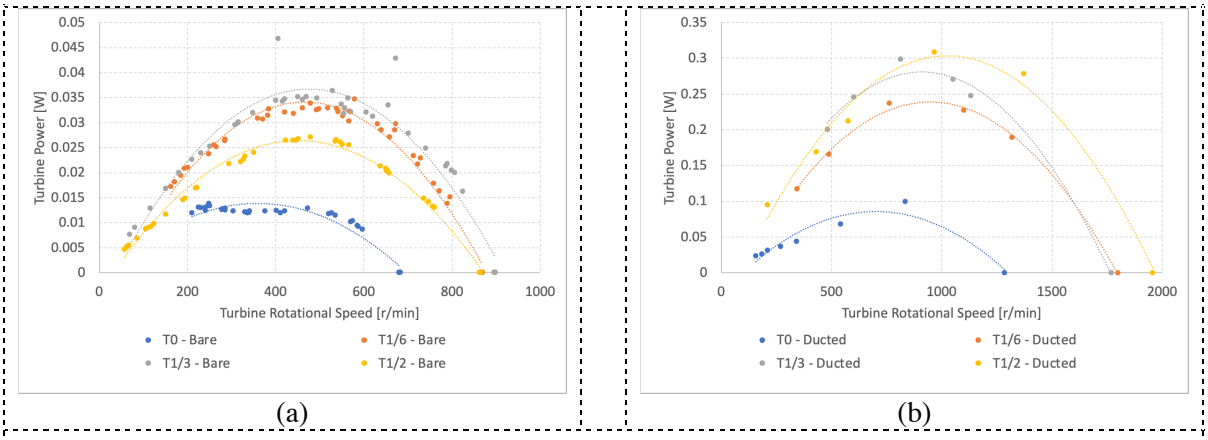

Figure 6. Turbine power for different turbine overlap ratios: (a) bare, (b) ducted.

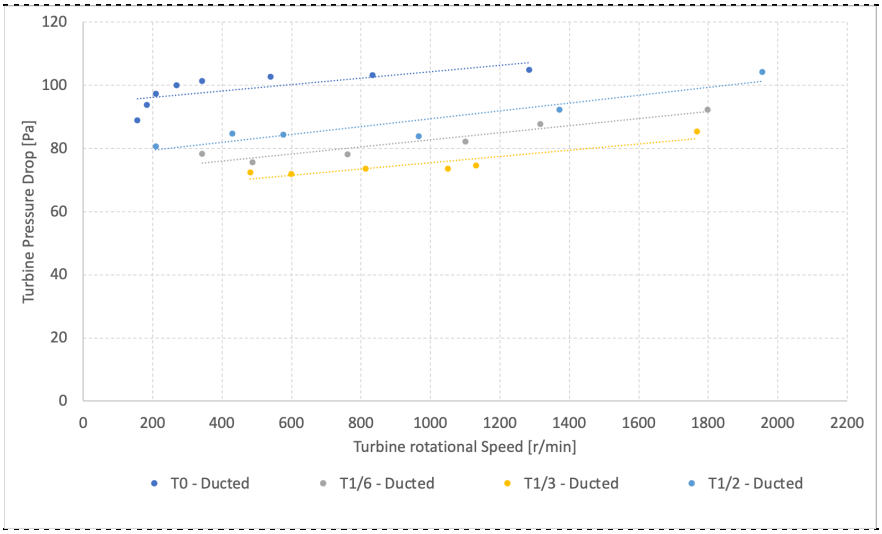

Figure 7. Pressure drop across ducted turbine for different turbine overlap ratios.

Once again, the explanation of this behavior is due to the different proportion between the two energy contributions: kinetic and manometric. The manometric contribution in ducted configuration is due to the blockage effect caused by the turbine rotation and friction as discussed by Pirozzoli et al. [29].

While 1/3 overlap ratio bare turbine presents the maximum kinetic contribution, this turbine in ducted configuration induces the lowest pressure drop and the minimum manometric contribution to the turbine, as it is possible to see in Figure 7.
On the contrary, although 1/2 overlap ratio bare turbine does not have the best performance, the same turbine, in ducted configuration, exploits the maximum manometric energy (see Figure 7).
As far as the turbine power coefficient is concerned, this was calculated as a function of turbine tip speed ratio using Eq. 1 and Eq. 2 [31, 32].

$$C_p = \frac{P_T}{\frac{1}{2}\rho\,\Omega_T\,V_0^3 + \Delta p\,\Omega_T\,V_0} \tag{1}$$

$$\lambda = \frac{\omega\,D}{2\,V_0} \tag{2}$$

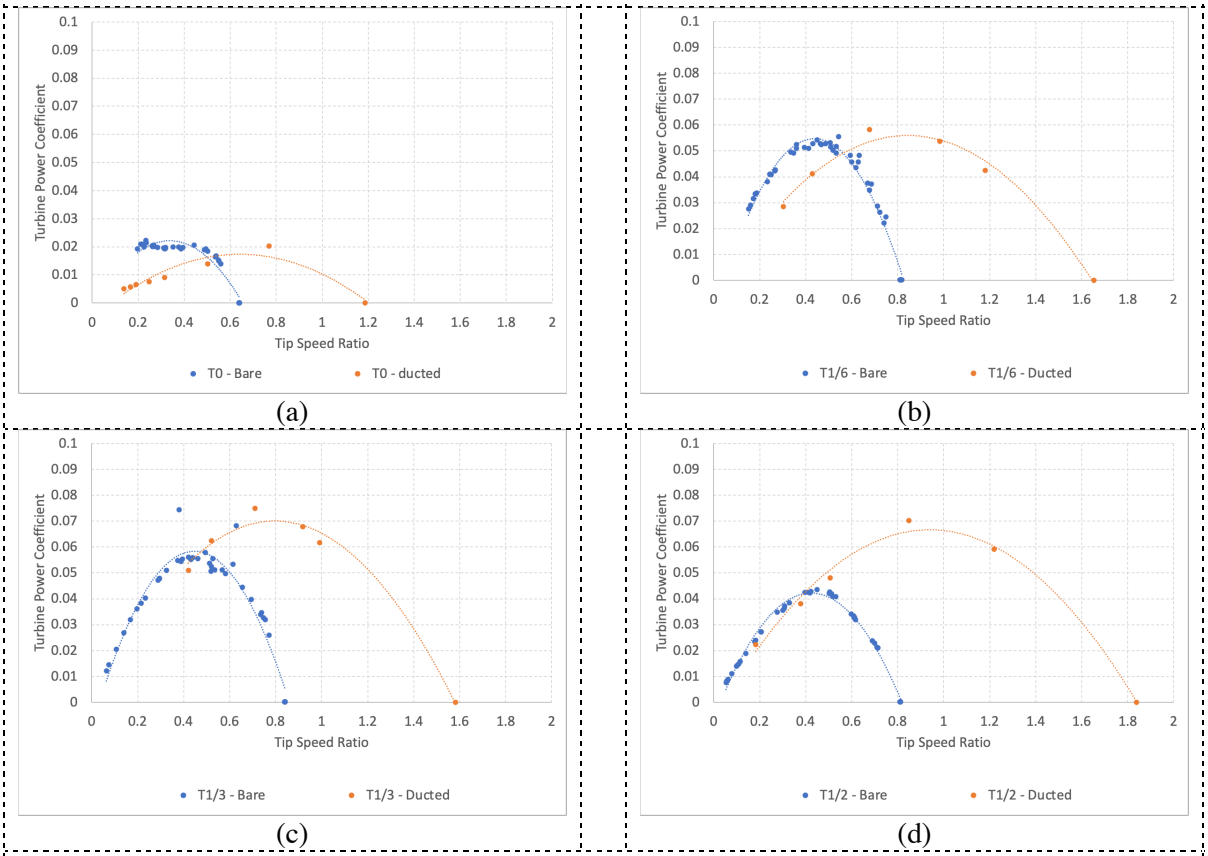

Figure 8. Turbine power coefficient for different turbine overlap ratios in both ducted and bare configurations: (a) OR = 0, (b) OR = 1/6, (c) OR = 1/3, (d) OR = 1/2.

In Figure 8 the power coefficient of bare and ducted turbines was compared; in Figure 9(a) a comparison on power coefficient of bare turbines is shown, while Figure 9(b) a comparison on power coefficient of ducted turbines is shown.
As it is shown in Figure 8, ducted turbine power coefficient increases with overlap ratio, and it is higher than bare turbine one for some of the studied overlap ratios. A wider range of tip speed ratio is also evident for ducted turbine (about twice).
This behaviour seems to be due to two main effects: increase of generated power and variation of induced pressure drop.

Comparing ducted turbine power coefficient as a function of the overlap ratio (see Figure 9(b)), it is clear that the best turbine performance was obtained by the one with an overlap ratio of 1/3.
A comparison between the graphs in Figure 6(b) and Figure 9(b) highlights that different overlap ratio allows best performance in terms of power and power coefficient. This discrepancy is probably due to the effects of turbine induced pressure drop [29] that act as an increaser in power production, while as a down counter in the turbine efficiency. This means that turbine with an overlap equal to 1/2 uses more efficiently manometric contribution in the input energy, while the turbine with an overlap ratio of 1/3 and 1/6 are not able to convert efficiently that contribution into power.

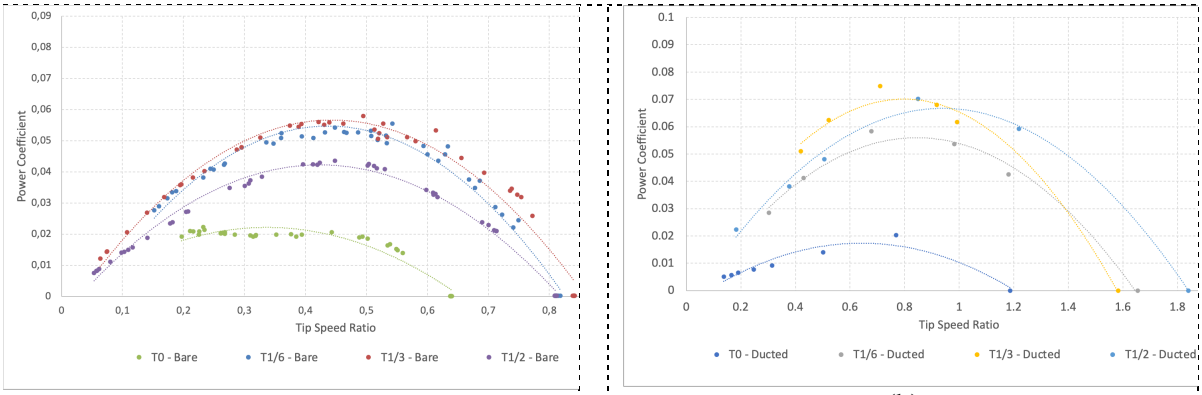

Figure 9. Turbine power coefficient for different turbine overlap ratios: (a) bare, (b) ducted.

5. Conclusions

In the present work an experimental parametric study on ducted Savonius air turbine performance was carried out. The effects of overlap ratio on turbine power, torque and power coefficient were analysed at fixed input air velocity. The results were compared to bare turbine experimental measurements to demonstrate how the duct affects the turbine performance. Also, four overlap ratios were tested: 0, 1/6, 1/3 and 1/2. This was done to have a comprehensive set of measurements on different configurations for a much more meaningful comparison.
An ad hoc experimental setup was designed to measure ducted turbine performance, while bare turbine performances were measured using a wind tunnel.
Based on the results presented in the paper, it is possible to draw the following conclusions:

1. The ducted turbine power is higher of about ten times than bare turbine power at all studied overlap ratios;
2. The ducted turbine presents a wider range (about twice) of tip speed ratio than the bare one;
3. In ducted configuration, best performances (both generated power and turbine power coefficient) were obtained using a turbine with an overlap ratio equal to 1/3, while, in bare configuration, best performances were obtained using a turbine with an overlap ratio between 1/6 and 1/3.

Finally, this work demonstrates that the ducted configuration can be a very attractive solution to highly improve the efficiency of Savonius rotors in all the applications in which it is possible to build the related apparatus. For instance, in urban environment. Furthermore, in oscillating water column wave energy converters, where the duct is already an inherent component of the energy conversion system, this solution could be very interesting compared to the more complex and expensive Wells and impulse turbines. This will be assessed in future research.

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