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# Experimental investigation on the effect of the duct geometrical parameters on the performance of a ducted wind turbine

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**Abstract.** This paper reports an experimental investigation on the effect of the duct geometry on the aerodynamic performance of an aerofoil shaped ducted wind turbine (DWT). The tested two-dimensional model is composed of an aerofoil equipped with pressure taps and a uniform porous screen. The experimental setup is based on the assumption that the duct flow is axisymmetric and the rotor can be simulated as an actuator disc. Firstly, different tip clearances between the screen and the aerofoil are tested to point out the influence of this parameter on the DWT performance in terms of aerofoil pressure distribution, aerofoil lift and flow field features at the duct exit area. Then, the combined effect of tip clearance, of the angle of attack and of the screen position along the aerofoil chord is evaluated through a Design of Experiments (DoE) based approach. The analysis shows that, among the analysed range of design factor variation, increasing angle of attack and the tip clearance leads to a beneficial effect on the lift and back-pressure coefficients, while they show a poor dependence upon the screen axial position. Finally, the configuration characterized by the maximum value of all three main factors (15 degree of angle of attack, 5% of tip clearance and 30% backward to the nozzle plane), has the best values of lift coefficient and back-pressure coefficient.

## Nomenclature

|            |   |                                   |
|------------|---|-----------------------------------|
| $L$        | = | lift                              |
| $V_0$      | = | free-stream velocity              |
| $c$        | = | chord                             |
| $p_0$      | = | pressure at the far wake          |
| $p_{exit}$ | = | pressure at the duct outlet plane |
| $C_T$      | = | thrust coefficient                |
| $C_{pe}$   | = | drag coefficient                  |
| $C_l$      | = | lift coefficient                  |
| AOA        | = | angle of attack (degr.)           |



$\Delta T$  = tip clearance  
 $Re$  = Reynolds number

## 1. Introduction

Ducted wind turbines (DWT) or diffuser augmented wind turbines (DAWT) increase the power output with respect to bare wind turbines by enhancing the mass flow passing through the turbine. This is obtained by using an aerodynamically shaped circular wing around the rotor. Several publications have focused on the study of different aerofoil shaped ducts and their effects on the performance of a wind turbine [1–5].

In the study of DWT, frequently the actuator disc assumption is used to model the same pressure drop as caused by the turbine blades. In wind tunnel experiments, the rotor is replaced by a uniform porous screen across which a pressure drop is explicitly imposed. This simplification makes it a useful tool during the preliminary design stage. It does not, however, capture potentially interesting aspects of the flow physics near the blade and in the wake of a DWT. In addition, the actuator disc model cannot predict the effect of the turbine wake on flow separation along the walls of the duct. This effect is negligible in the study when the investigation concentrates on the duct rather than rotor performance.

Hansen et al. [1] studied an aerofoil shaped duct with the suction side oriented towards the centreline, with modelling the rotor as an actuator disc. They concluded that a larger thrust is obtained compared with a straight duct, leading to an increased mass flow through the rotor. Franković and Varsalović [2] concluded that an aerofoil shaped duct can improve the energy output of a conventional turbine by a factor of 3.28, thus resulting in an economic benefit of about five times. It's noted that the additional cost of duct is not taken into account for this economic index.

The performance of aerofoil shaped DWT is affected by three design features: the rotor geometry, the tip clearance (the gap between the tip of the blade and the inner surface of the duct or diffuser) and the duct geometry. Several studies on tip clearance effects have been carried out in the field of turbomachinery [6,7], and the effects are also expected to be the same for DWT's.

Spencer [8] investigated the effect of the tip gap in a four bladed axial water pump. The tip clearance varied from 0.6 to 2.4 % of the blade length. The results show that as the tip gap is enlarged there is an initial increase of the efficiency followed by a steady decrease. The existence of an optimal tip gap, larger than the minimum manufacturing spacing, is confirmed by other researchers [6–9]. Peacock [7] stated that the best tip gap is the one for which the opposing effects of secondary flows and tip leakage with rotor/wall relative movement are balanced. Mathis [6] analysed the losses associated with the rotor, and reported that flow leaks across the tip gap from the pressure to the suction side, cause a tip vortex at the blade tip and lower the pressure difference between the suction and pressure sides. This behaviour is almost the same for a DWT. Foreman [10] tested a DAWT with large blade tip gap ( 4% of the rotor radius) which allows a greater degree of eccentricity or deformation of the diffuser without the hazard of contacting the rotating blades. Gomis [11] numerically studied the influence of the tip clearance on a DAWT, and obtained an recommended tip gap dimension (10.5% of the blade length) for this particular truncated cone shaped duct and rotor model. Nevertheless, a large tip gap increases the thrust on the duct thus generating a bulky DWT structure.

To counteract the above-mentioned large-tip-gap effect, the Grumman Aerospace proposed to use boundary layer control techniques on the duct, i.e. a multi-slotted DAWT [12]. The principle of the boundary layer control technique of the multi-slotted DAWT is to generate cavities, which eliminate losses associated with high velocities in restricted passages. The ability to employ additional boundary layer control slots enables the blade tip-gap/inlet slot to be reduced to 1.5% of the rotor radius. The smaller gap is expected to reduce blade tip losses whilst maintaining sufficient clearance from the diffuser so that structural cost penalties are not incurred. However, the velocity used by the Grumman Aerospace researchers to represent the average velocity across the blade plane was overestimated. They used the velocity near the blade tips as the representative velocity for calculating the average

velocity at the blade plane. Overall, Igra's [13] results show that with proper treatment of tip clearance, an increase in diffuser efficiency and augmentation can be achieved for a given model geometry.

Based on the preceding research, the tip clearance is usually chosen equal to 3% of the rotor radius in order to minimize tip losses [14] which is larger than the one used for turbomachinery blades, (e.g. 1% to 3% of blade tip chord) [15]. It can be inferred that using the analysis method outlined by Lilley & Rainbird [16], the loss in rotor efficiency associated with the tip clearance on the multi-slotted DWT would be around 1% and therefore negligible. This benefit of DWTs to blade performance has also been noted by Gilbert et al. [14], Iwasaki [17], de Vries [15] and Yeung as referenced in [18]. Finally, it should be stressed that the tip clearance effect and vortex structures originating from a rotating-blade tip, are thoroughly different from that of an actuator disc based approach.

In addition to the tip clearance effect on an aerofoil shaped DWT performance, the angle of attack of the duct and the rotor position are believed to play an important role. In absence of flow separation, an high angle of attack leads to more mass flow through the duct [4]. By a 2D DAWT numerical study, Venters [19] found out that the wake expansion caused by the rotor favors the flow to be attached to the diffuser inner surface and allows the angle of the diffuser to be higher than the isolated diffuser. It can be easily found that varying the angle of attack leads to different area ratio, between the duct exit area and throat area, and back pressure of the duct. Physically increasing the area ratio induces a larger mass flow through the turbine. Widnall [20] put an additional porous plate at the trailing edge plane, inspired by a previous study in which a solid brim was placed at the exit [21], and obtained almost doubled power output of the wind turbine for the control duct in both analytical method and experiments.

In light of these previous studies, the effect of the tip clearance, angle of attack and rotor position on design tolerances needs to be determined for a DWT. To the best of the author's knowledge, the variation in the flow field with these three factors together has not been experimentally investigated for an aerofoil-shaped DWT. Though the screen generates different vortex structures at the tip. However, since this study is focused on a preliminary design stage, the peculiarities of the vortex structures will not be analysed. Therefore the rotor is replaced by a uniform porous screen. In order to give an insight into the influence of the tip clearance, angle of attack and the screen position on the DWT performance in the fluid field, the thrust on the screen and pressure distribution along the aerofoil model, as well as development of the downstream flow are examined.

Sections 2 of this paper briefly introduces the philosophy of the analytical approach, design of experiment, section 3 describes the experiment method. Section 4 presents the blockage correction method adopted in this study. Section 5 shows the lift coefficient and back pressure coefficient from different test rigs first. Second, the pressure profiles on related test cases are also discussed. Then the approach of the Design of Experiment is used to get further analysis of the effect of duct geometry on the model performance. The paper ends with conclusions drawn from this research.

## 2. Analytical framework

### 2.1 Parameters of interest

It is well known that the mass flow increase provided by the duct depends on four factors: the duct area ratio, the flow separation from the duct surface, the back-pressure reduction at the duct exit, and viscous losses. In this study two parameters, lift coefficient and back pressure coefficient, are chosen to evaluate the DWT performance, since these two parameters are directly related to the induced mass flow. The section lift coefficient is calculated with equation (1).  $v_0$  and  $c$  are the freestream velocity and the aerofoil chord length, respectively.

$$C_l = \frac{L}{\frac{1}{2} \rho v_0^2 c} \quad (1)$$

Van Bussel [22] proposed that reducing back pressure behind the exit of a DWT has beneficial effect on the performance. The pressure difference between the far wake ( $p_0$ ) and the duct outlet ( $p_{exit}$ ) is parameterized as a back-pressure coefficient.

$$C_{pe} = \frac{p_{exit} - p_0}{\frac{1}{2} \rho v_0^2} \quad (2)$$

It can be seen the back pressure coefficient is related to the duct shape and the pressure drop caused by rotor. Moreover, the amount of extra back pressure can be obtained at the duct exit depends on the development of the boundary layer along the inner side of the duct. Hence, the viscous effects and possible early flow separation at the duct surface will impact the back pressure. In all, since a reduction of  $C_{pe}$  leads to more flow through the turbine, this study takes  $C_{pe}$  as one of the indicators to evaluate the performance of ducted wind turbine.

## 2.2 Design of Experiments (DoE)

In addition to the direct analysis from the measured data, the combined effect of the tip clearance, of the screen horizontal position and of the angle of attack is evaluated through a Design of Experiments (DoE) based approach. It is based on the use of orthogonal arrays, which leads to the evaluation of the effect of a single design factor averaged out while changing, with the same frequency, the levels of all other design parameters. By doing so, it is also possible to ascertain if an interaction between two or more factors exists, i.e., if the mean effect of one factor depends upon the level of the other factors. Moreover, thanks to established statistical methods, the significance of all design parameters and of their interactions can be easily evaluated, thus providing useful information to reduce the number of design variables to be used in a more expensive optimization procedure. Details about the DoE technique can be found in standard textbooks [23–26].

The performance of the ducted screen is analyzed by evaluating the effects of three different geometrical parameters on the aerofoil lift and back-pressure coefficient. In particular, the selected design factors are the aerofoil angle of attack (factor A), the horizontal screen position (factor B), and, finally, the tip clearance (factor C). Three levels of each parameter are tested (denoted as -1, 0 and +1 in Table 1).

**Table 1.** Factors and levels.

| A(AoA)            |                  |                   | B(x/ch)           |                  |                   | C( $\Delta T$ )   |                  |                   |
|-------------------|------------------|-------------------|-------------------|------------------|-------------------|-------------------|------------------|-------------------|
| A <sub>(-1)</sub> | A <sub>(0)</sub> | A <sub>(+1)</sub> | B <sub>(-1)</sub> | B <sub>(0)</sub> | B <sub>(+1)</sub> | C <sub>(-1)</sub> | C <sub>(0)</sub> | C <sub>(+1)</sub> |
| 5°                | 10°              | 15°               | -20%              | 0%               | 30%               | 1%                | 3%               | 5%                |

The nozzle plane ( $B_{(0)}$ ) is at the chord-wise position where the thickness of the duct aerofoil is maximum, i.e. the throat of the duct. The screen is also moved forward (resp. backward) to 20% (resp. 30%,) of the axial distance between the aerofoil leading edge and the nozzle plane (see Figure 1(b)). The tip clearance variation is realized by moving the aerofoil in vertical direction, and keeping fixed the screen length, i.e. the blade radius. Therefore, the DWT model has variable duct exit area. As reported in Table 1, the gap between the screen and the aerofoil will be changed from 1% of the screen length to 5%, with a step of 2%.

From a preliminary DoE analysis with three-levels parameters, no significant curvatures have been addressed in the main factors effects. So that, for the sake of brevity, a two levels (-1 and +1) DoE analysis is carried out in this paper. In particular, eight ( $2^3$ ) different geometries can be obtained combining three factors with two levels, so that the classical  $L_8$  full factorial plane, testing all possible combinations of factors and levels, has been adopted (see Table 2).

**Table 2.** Full factorial plane for lift and back pressure coefficient analysis.

|   | A<br>(AoA) | B<br>(x/ch) | C<br>( $\Delta T$ ) | AB | AC | BC | ABC | $C_l$ | $C_{pe}$ |
|---|------------|-------------|---------------------|----|----|----|-----|-------|----------|
| 1 | -1         | -1          | -1                  | 1  | 1  | 1  | -1  | 1.236 | -0.780   |
| 2 | -1         | -1          | +1                  | 1  | -1 | -1 | 1   | 0.989 | -0.807   |

|      |    |    |    |    |    |    |    |        |        |
|------|----|----|----|----|----|----|----|--------|--------|
| 3    | -1 | +1 | -1 | -1 | 1  | -1 | 1  | 1.500  | -0.757 |
| 4    | -1 | +1 | +1 | -1 | -1 | 1  | -1 | 0.662  | -0.800 |
| 5    | +1 | -1 | -1 | -1 | -1 | 1  | 1  | -0.021 | -1.208 |
| 6    | +1 | -1 | +1 | -1 | 1  | -1 | -1 | -0.138 | -1.229 |
| 7    | +1 | +1 | -1 | 1  | -1 | -1 | -1 | 0.049  | -1.158 |
| 8    | +1 | +1 | +1 | 1  | 1  | 1  | 1  | -0.463 | -1.278 |
| Mean |    |    |    |    |    |    |    | 0.477  | -1.002 |

All possible geometrical configurations are reported in the eight rows of the table, whereas the first seven columns represent a design parameter or interaction. Hence, the ( $m$ -th,  $n$ -th) entry is the level of the  $n$ -th parameter in the  $m$ -th test. Also note that, the three main factors (A, B and C) are allocated in the first three columns of the factorial plane, whereas the first, second and third order interactions are assigned to the other columns according to the classical interaction-assignment rules [25]. For each of the tested configurations, the value of the aerofoil sectional lift and back pressure coefficients are listed in the last two columns, respectively. The arithmetic mean over all tests of the response variables ( $C_l$  or  $C_{pe}$ ) is also reported in the last two columns.

Table 2 can be also used to evaluate the mean effect of each factor. More in detail, the mean effect of the A factor at level +1 is the difference between the mean value of the response variable ( $C_l$  or  $C_{pe}$ ) when the A level is set to +1 and the overall mean, that is

$$Eff(A_{+1}) = \frac{1}{4} \sum_{m=5}^8 C_{l,m} - \bar{C}_l \quad (3)$$

where  $m$  is the test number. The same equation can be applied to the back pressure coefficient. Also note that

$$Eff(A_{-1}) = \frac{1}{4} \sum_{m=1}^4 C_{l,m} - \bar{C}_l = -Eff(A_{+1}) \quad (4)$$

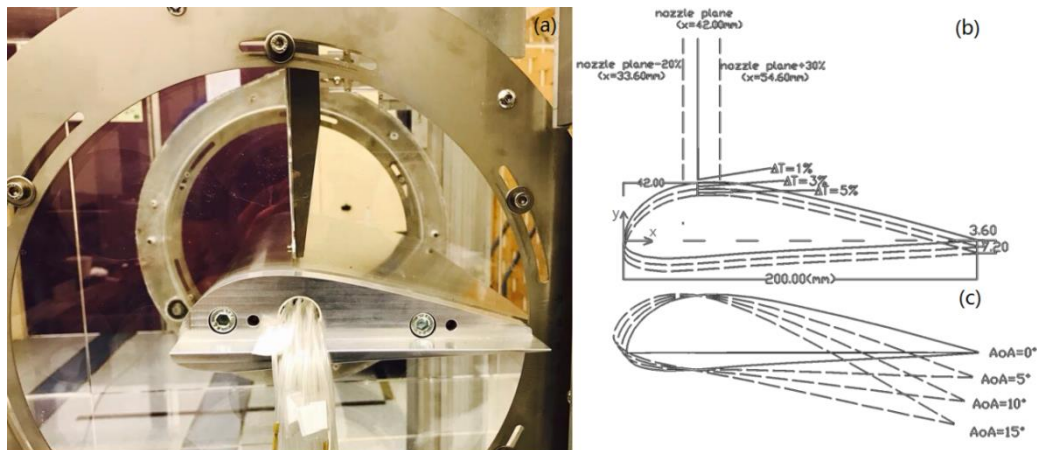
so that the mean effect of the factor A is generally cast in the following form:

$$Eff(A) = Eff(A_{+1}) - Eff(A_{-1}) \quad (5)$$

### 3. Experimental setup

The wind tunnel is an open-circuit low-speed wind tunnel with a test section of  $0.4 \text{ m} \times 0.4 \text{ m} \times 1.5 \text{ m}$ . The maximum freestream velocity in the test section is 35 m/s. To ensure good flow quality in the test section, the tunnel settling chamber contains a thick honeycomb and anti-turbulence screens, resulting in a turbulence level less than 0.5% over the Reynolds number tested. For a nominal test-section speed of 23.2 m/s, a Reynolds number of  $3.0 \times 10^5$  based on an aerofoil chord of 0.2 m is realised. The freestream dynamic pressure is determined from a pitot probe in the settling chamber.





**Figure 1.** Model setup. (a) aerofoil model setup with a porous screen in test; (b) screen position movement in X direction; (c) angle of attack variation in different test configurations.

A two-dimensional configuration is tested, as shown in Figure 1(a). This model is chosen based on the assumption that a duct flow is axisymmetric, thus only half part duct needs to be built. The setup is made of an aerofoil type and a uniform porous screen, the tunnel upper wall is used as a symmetry plane. The screen porosity is chosen such to generate a pressure drop similar to the one obtained across the rotor of the commercial Donqi wind turbine [27]. The axial force on the screen  $T$ , across which a pressure drop is explicitly imposed, is expressed by the thrust coefficient  $C_T$ :

$$C_T = \frac{T}{\frac{1}{2} \rho v_0^2 A_s} \quad (6)$$

Where  $\rho$  is the fluid density,  $v_0$  is free-stream velocity and  $A_s$  is the screen area. The thrust coefficients of the screen experienced in this study is  $C_T = 1.46$ .

The aerofoil model is mounted horizontally, covering the entire span of the test section. The thrust on screen is acquired by a six-component balance system. The lift and drag on the aerofoil is obtained by the pressure taps on the aerofoil and wake rake, which is put behind the trailing edge for 3 times of the chord length.

As previously stressed, three tip clearances are tested: 1%, 3% and 5% of the screen length, that is the screen dimension in vertical direction, displayed in Figure 1(b). the latter also shows the three investigated screen positions: nozzle plane, 20% forward of the nozzle plane and 30% backward of the nozzle plane. Finally, the angle of attack varies from 0 degree to 15 degree, with steps of 5 degree (see Figure 1(c)).

#### 4. Wind tunnel blockage corrections

The presence of the wind tunnel walls increases the measured lift and drag because of the increase in velocity perceived at the model. The measured quantities that must be corrected can be sub-divided into two categories: stream and model quantities. The most important stream quantity is the velocity at the model. This velocity is obtained from the free-stream velocity measurements and by applying the proper corrections to account for solid and wake blockage as well as boundary-layer growth [28].

The model quantities of interest are the lift, drag and angle of attack, which are corrected in their non-dimensional form to account for solid and wake blockage as well as streamline curvature. It is important to note that the use of drag data is required to correct the model quantities since wake blockage is proportional to the measured drag coefficient.

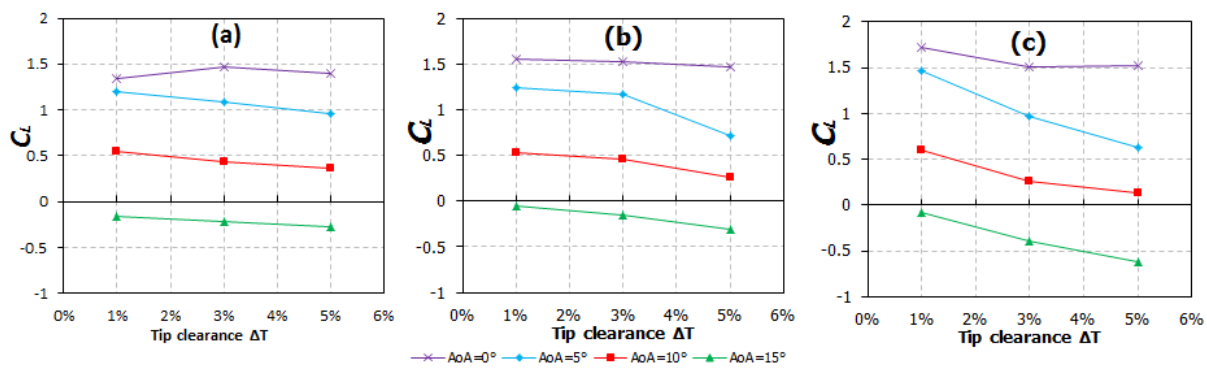
It's aware of the fact that the flow field of aerofoil plus screen model is different from the flow field of two separate components. Nevertheless, when the individual effects promoted by the interference between the walls and the aerofoil, and the screen are known, the total alteration in the flow at the aerofoil is found by superposition. The characteristics of the aerofoil in the altered field of



flow are compared with the characteristics in free air. The method of superposition, which is fundamental to the entire analysis, is in general inapplicable to compressible flow as the differential equation for such flow is nonlinear in the physical plane. The separate solutions are superposed by assuming the induced velocities are small as compared with the velocity of the undisturbed flow. Since the current experiments are conducted in low Reynolds number, namely, superposition of velocities is, in this case, technically permissible. Furthermore, the tunnel-wall corrections are in most cases rather small relative to the experimental quantities being corrected, so that it is not thought that the use of this approximate method will lead to large errors in the final corrected quantities. All the results presented in the next section are corrected.

## 5. Experimental results and discussion

Firstly, the effect of varying the tip clearance ( $\Delta T$ ) and the angle of attack (AoA) on the performance of the DWT model is assessed by calculating the lift coefficient ( $C_l$ ), as shown in Figure 2.



**Figure 2.** Effect of the tip clearance on the lift coefficient of the aerofoil (a) screen at the nozzle-20% plane; (b) screen at the nozzle plane; (c) screen at the nozzle+30% plane.

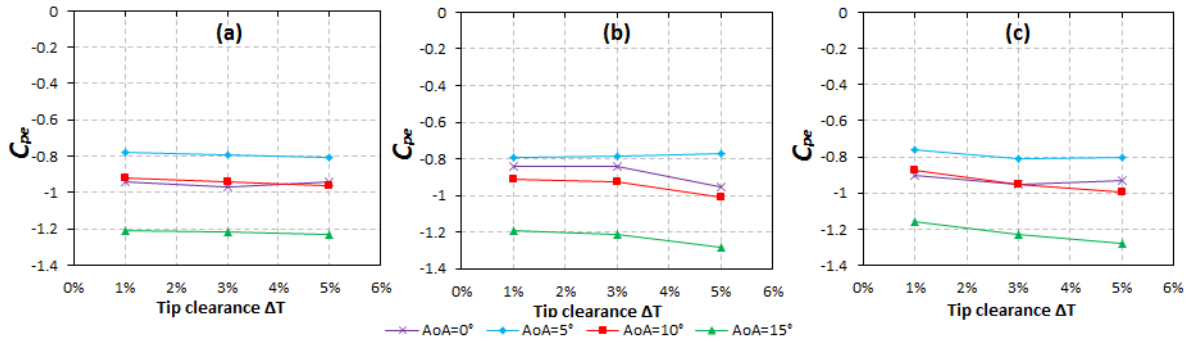
The negative (positive)  $C_l$  in Figure 2 stands for the lift directs towards (outwards) the screen symmetry axis, which is beneficial (detrimental) for the rotor mass flow increase [15]. This can be better understand inspecting, for example, the pressure coefficient distribution for the case  $AoA = 0^\circ$  which has a positive  $C_l$ . Figure 4 shows that, for this configuration, the pressure on the aerofoil inner side (the one where the screen is installed) is always greater than that on the outer side. This is because the outer pressure coefficient is always more negative in comparison with the inner one. Consequently, the outer (inner) surface is the aerofoil suction (pressure) side and the lift is directed outwards the inner region. This also means that the aerofoil bound circulation at the leading edge is directed from the inner to the outer side, thus inducing a decrease in the rotor mass flow. From Figure 2, the  $C_l$  consistently becomes negative by increasing the AoA and  $\Delta T$ , which is ascribed by the fact that with the enlarging  $\Delta T$  the wake on the screen tip mixes more incoming flow, thereafter, velocity at the screen tip becomes more uniform and the wake is enlarged. A large wake divergence leads to lower pressure at the duct exit, eventually more mass flow rate will be drawn into the duct.

In Figure 2, it is also found that the  $C_l$  is sensitive to the AoA variation, and it is not sensitive to the screen position. Among the tested cases, the best  $C_l$  is obtained when the AoA is set to 15 degree, the  $\Delta T$  is 5% of the blade length and the screen is put at 30% backward of the nozzle plane.

As mentioned before, little effect of the screen axial position on  $C_l$  is found. In general, when  $\Delta T$  is large (e.g. 5% of screen length), moving the screen towards to the trailing edge has positive effect on the  $C_l$ . This can be explained by the increase of the velocity behind the screen in the duct divergence area, which effectively enlarges the pressure differences between the inner and outer side.

Since the back pressure coefficient ( $C_{pe}$ ) is proportional to the power coefficient [29], the  $C_{pe}$  of the tested DWT model is also analysed (Figure 3). It can be seen that a lower  $C_{pe}$ , which corresponds to a beneficial effect on the rotor mass flow, is realized with increasing AoA. Note that the data

presented in this study have been corrected for blockage effects though, the single components contribution to this large back pressure value has not been quantified yet.

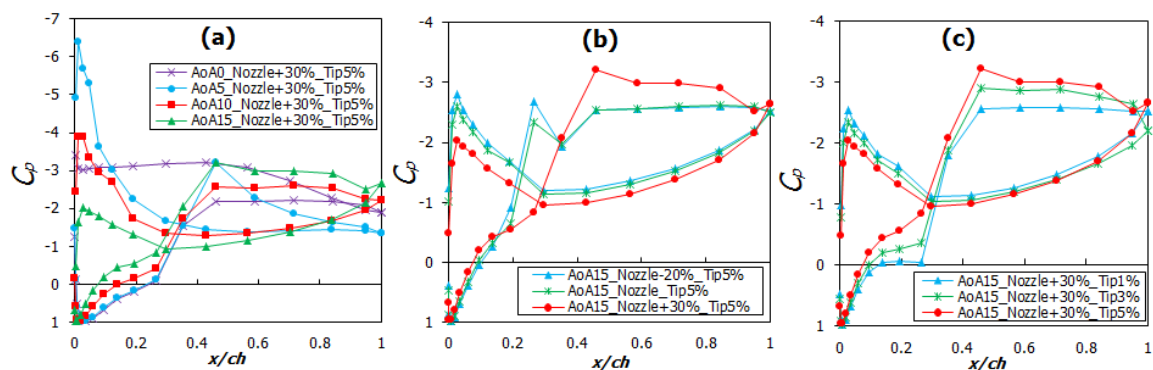


**Figure 3.** Effect of the tip clearance on the back pressure coefficient of the DWT model (a) screen at the nozzle-20% plane; (b) screen at the nozzle plane; (c) screen at the nozzle+30% plane.

As previously highlighted, Figure 3 shows that, the model is characterised by a lower value of  $C_{pe}$  by increasing the AoA. Likewise, increasing the  $\Delta T$  presents no prominent influence on the  $C_{pe}$  performance, in particular with the screen at the location before nozzle plane, as shown in Figure 3(a). However, Figure 3(b) and Figure 3(c) reveal that moving the screen from the nozzle plane toward the trailing edge generates lower  $C_{pe}$ . It is owing to the fact that moving the screen backward is favourable for creating more negative area behind the screen, as the pressure plots shown in Figure 4 (b).

It has to be stressed again that, by assuming the flow is one-dimensional throughout, thus the magnitude of  $C_{pe}$  in this study is constant. In practice, the radial distribution of velocity (pressure) at the rotor plane or duct exit plane is non-uniform, the velocity (pressure) near to the duct inner surface is higher (lower) than at the centre axis [30].

Since Figure 2 and Figure 3 illustrate that the best  $C_l$  is achieved by setting the AoA at 15 degree and locate the screen at the nozzle + 30% plane, the pressure profile related to this configuration are therefore investigated. The pressure distribution ( $C_p$ ) along the aerofoil as affected by the AoA and  $\Delta T$  is displayed in Figure 4.



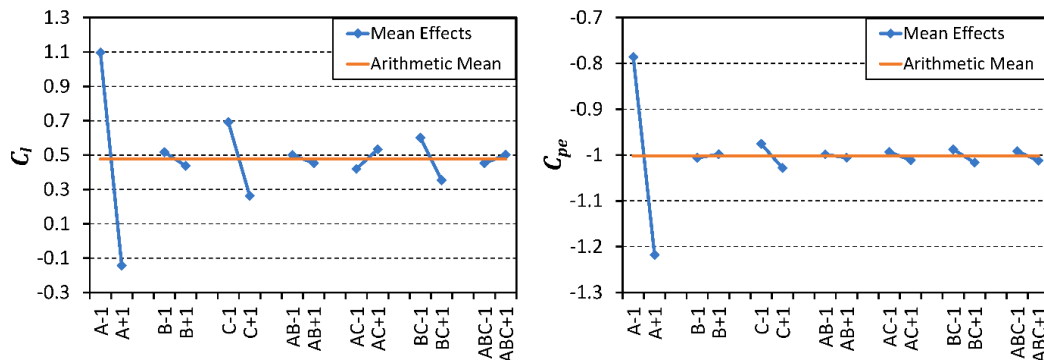
**Figure 4.** Pressure coefficient distribution along the aerofoil for (a) different Angle of Attack; (b) different screen position; (c) different tip clearances.

There are noticeable variations on the pressure drop for different AoA and  $\Delta T$ , although the AoA is the more significant factor. In Figure 4(c), a lower  $C_p$  is achieved on the inner side with increasing  $\Delta T$ . Moreover, Figure 4(c) also shows that a minor pressure gradient variation on the inner side, starts from  $x/ch = 0.5$ , for all three different  $\Delta T$ . It implies the separation presence and it can be expected that by increasing the  $\Delta T$  (case of  $\Delta T=5\%$  in Figure 4(c)), the effect of boundary layer growth over the screen

tip revealed a possible reduction effect of separation loss. The results that have been presented here suggested increasing the aft loading of the aerofoil would be beneficial for the  $C_l$  enhancement.

## 6. Design of Experiments (DoE) analysis of the duct geometry effect

In this section, the DoE (Table 2) is applied to evaluate the effect of the three geometrical parameters on the performance of the ducted screen. Table 2 shows that configuration #8 has the Best values of  $C_l$  and  $C_{pe}$ . The mean effect of the design factors on the  $C_l$  and  $C_{pe}$  are shown in Figure 5 left and right, respectively.



**Figure 5.** Mean effects of the design parameters and interactions on the lift (left) and back-pressure (right) coefficients.

Inspecting the figure, it can be easily inferred that a beneficial effect on both  $C_l$  and  $C_{pe}$  can be obtained by increasing the AoA and the  $\Delta T$ . For the sake of brevity, a thorough analysis of the interaction is not shown hereafter. However, for the  $C_{pe}$ , the effect of the simultaneous increase of these two factors is magnified by the synergistic interaction existing between them. Contrarily, for the  $C_l$ , the effect of the simultaneous increase in factor A and C is reduced by their interaction. Finally, increasing the screen axial position has a beneficial (detrimental) effect on the  $C_l$  ( $C_{pe}$ ). The mean effect of factor B is, however, very small.

To evaluate the significance of all factors and interactions, the very simple Pareto-ANOVA method [25], based on the well-known Pareto principle, is adopted. The results of this analysis are reported in Table 3 and Table 4 for the  $C_l$  and  $C_{pe}$ , respectively. Rows one and two of Table 3 (resp. Table 4) represent the sum of the  $C_l$  values (resp.  $C_{pe}$ ) when the corresponding factor or interaction is set at level -1 and +1, respectively.

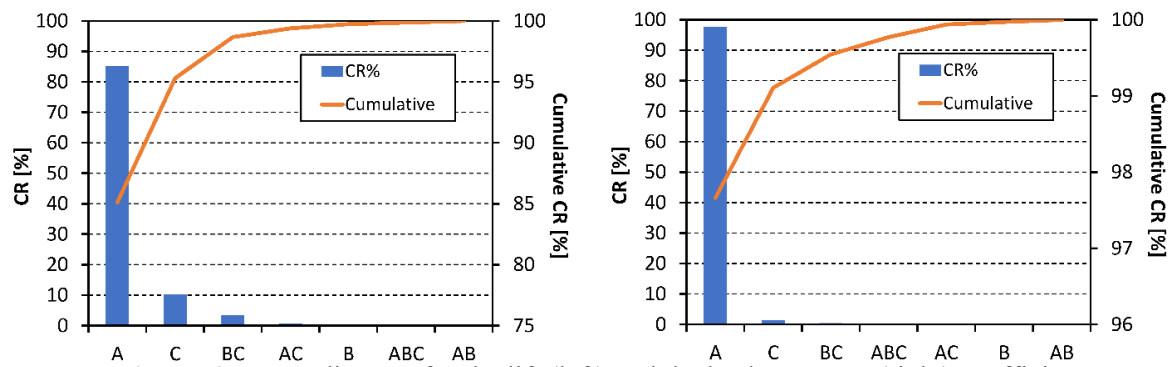
**Table 3.** Pareto – ANOVA table for the lift coefficient.

|                 | A<br>(AoA) | B<br>(x/ch) | C<br>( $\Delta T$ ) | AB   | AC   | BC   | ABC  | Total  |
|-----------------|------------|-------------|---------------------|------|------|------|------|--------|
| Sum at Level -1 | 4.39       | 2.07        | 2.76                | 2.00 | 1.68 | 2.40 | 1.81 | 17.11  |
| Sum at Level +1 | -0.57      | 1.75        | 1.05                | 1.81 | 2.13 | 1.41 | 2.00 | 9.59   |
| SSQ             | 24.60      | 0.10        | 2.94                | 0.04 | 0.21 | 0.97 | 0.04 | 28.91  |
| CR [%]          | 85.12      | 0.35        | 10.19               | 0.13 | 0.72 | 3.36 | 0.13 | 100.00 |

**Table 4.** Pareto – ANOVA table for the back-pressure coefficient.

|                 | A<br>(AoA) | B<br>(x/ch) | C<br>( $\Delta T$ ) | AB    | AC    | BC    | ABC   | Total  |
|-----------------|------------|-------------|---------------------|-------|-------|-------|-------|--------|
| Sum at Level -1 | -3.14      | -4.02       | -3.90               | -3.99 | -3.97 | -3.95 | -3.97 | -26.96 |
| Sum at Level +1 | -4.87      | -3.99       | -4.11               | -4.02 | -4.04 | -4.07 | -4.05 | -29.16 |
| SSQ             | 2.98       | 0.00        | 0.04                | 0.00  | 0.01  | 0.01  | 0.01  | 3.06   |
| CR [%]          | 97.66      | 0.03        | 1.44                | 0.03  | 0.17  | 0.44  | 0.23  | 100.0  |

The magnitude of the variation in the response variable associated to a factor or interaction is evaluated through the square of the difference (SSQ) between the first two rows (see the third row). Finally, the significance of a factor is measured with the help of the so-called contribution ratio (CR) defined as the ratio between the SSQ of the factor and the sum of the SSQ of all factors and interactions. Figure 6 reports the CR (left axis) in a descending order and the cumulative CR (right axis).



**Figure 6.** Pareto diagram for the lift (left) and the back-pressure (right) coefficients.

Inspecting Figure 6, it clearly appears that the AoA is the most significant factor which contributes to the 85.12% (resp. 97.66%) to the variation of  $C_l$  (resp.  $C_{pe}$ ) coefficient. The tip clearance is also weakly significant contributing to the 10.19% (1.44%) to the lift (back-pressure) coefficient variation. In the analyzed range of variation, the screen position and the interactions are not significant and they can be neglected if an optimization procedure has to be carried out, thus reducing the number of variables to be optimized.

## 7. Conclusions

In this paper the effects of the tip clearance, of the angle of attack and of the screen horizontal position on aerofoil performance are investigated and correlated with the flow behaviour around the aerofoil. It is important to note that, the conclusions presented below are limited to the specifications of this studied aerofoil model and screen, but they can be qualitatively applied also to the classical axisymmetric configuration.

The DWT performance is evaluated regarding to lift coefficient and back pressure coefficient as these two parameters are directly related to the ability to swallow more mass flow through the rotor. The analysis points out that increasing the angle of attack and tip clearance implies a performance enhancement of DWT. Moreover, in the analysed range of parameters variation, it is noted that the lift coefficient is sensitive to the variation of the Angle of Attack, and is not sensitive to the screen position. Among the tested cases, the best lift coefficient is obtained by setting the tip clearance as 5% of screen length, the angle of attack at 15 degree and the screen behind 30% of nozzle plane, which is further validated by the Design of Experiments analysis.

Increasing the angle of attack creates a lower value of back pressure coefficient. Though all data have been corrected in this study, blockage effect from each single variants is not yet clear.

The pressure distribution suggests that increasing the tip clearance is favourable for creating negative pressure zone behind the screen thus could induce an increased velocity through the rotor. In addition, the pressure profiles imply that increasing the aft loading of the aerofoil would be beneficial for the lift coefficient enhancement.

The combined effect of the tip clearance, of the screen horizontal position and of the angle of attack is evaluated through a Design of Experiments based approach. It infers that a beneficial effect on both lift coefficient and back pressure coefficient can be obtained by increasing the angle of attack and the tip clearance. For the back pressure coefficient, the effect of the simultaneous increase of these two factors is magnified by the synergistic interaction existing between them. Contrarily, for the lift

coefficient, the effect of the simultaneous increase in angle of attack and tip clearance is reduced by their interaction. As noted before, increasing the screen axial position has a beneficial (detrimental) effect on the lift (back pressure) coefficient, however the mean effect of this factor is very small.

Finally, the angle of attack is the most significant factor which contributes to the 85.12% (resp. 97.66%) to the variation of lift coefficient (resp. back pressure coefficient). The tip clearance is weakly significant contributing to the 10.19% (1.44%) to the lift (back pressure) coefficient variation. In the analyzed range of variation, the screen position and the interactions are not significant and they can be neglected if an optimization procedure has to be carried out, thus reducing the number of variables to be optimized.

Given the preceding studies, there is still a need for further aerodynamic studies, with higher spatial resolution, in order to better understand the behaviour of flow in the tip region and how this flow is related to mass flow rate. These studies are especially important in aerofoil shaped ducts that are representative of high-pressure wind turbines with relative motion simulation, where data are very scarce or non-existent.

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