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# Aerodynamic optimization of the blades of diffuser-augmented wind turbines

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ABSTRACT

Adding an exit diffuser is known to allow wind turbines to exceed the classical Betz–Joukowsky limit for a bare turbine. It is not clear, however, if there is a limit for diffuser-augmented turbines or whether the structural and other costs of the diffuser outweigh any gain in power. This work presents a new approach to the aerodynamic optimization of a wind turbine with a diffuser. It is based on an extension of the well-known Blade Element Theory and a simple model for diffuser efficiency. It is assumed that the same conditions for the axial velocity in the wake of an ordinary wind turbine can be applied on the flow far downwind of the diffuser outlet. An algorithm to optimize the blade chord and twist angle distributions in the presence of a diffuser was developed and implemented. As a result, an aerodynamic improvement of the turbine rotor geometry was achieved with the blade shape sensitive to the diffuser speed-up ratio. In order to evaluate the proposed approach, a comparison with the classical Glauert optimization was performed for a flanged diffuser, which increased the efficiency. In addition, a comparative assessment was made with experimental results available in the literature, suggesting better performance for the rotor designed with the proposed optimization procedure.



## 1. Introduction

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 cost-effective manner, as recently noted by Al-Sulaiman and Yilbas [1]. There is an extensive literature on diffuser-augmented wind turbine (DAWT) performance. Rio Vaz et al. [2] developed an innovative approach for the performance analysis of DAWTs based on blade element theory (BET), in which a more general semi-empirical one-dimensional analysis was carried out. Glauert's correction for the induction at high thrust was also employed. Their results yielded good agreement with experimental data. Most recently, Kosasih and Hudin [3] investigated the impact of turbulence intensity on micro wind turbine efficiency in converting the wind energy into power. The performance of bare micro wind turbine (MWT) and diffuser-augmented micro wind turbine (DAMWT) models subject to different levels of turbulence was reported. It was shown that shrouding the turbine with diffuser increases the power coefficient $C_P$ by a factor of almost two. Beyond a certain tip-speed ratio, the performance of both MWT and DAMWT was shown to decrease with turbulence intensity, however the $C_P$ of the DAMWT was still greater than that of the bare MWT wind indicating the diffuser augmentation was still achievable even at high freestream turbulence.

Jafari and Kosasih [4] performed a Computational Fluid Dynamics (CFD) study, where the augmentation is strongly dependent on the geometry of the diffuser, such as length and expansion angle. Also, they reported that a higher area ratio creates greater pressure reduction at the diffuser exit, which increases the mass flow rate, agreeing with Hansen et al. [5]. They employed a one-dimensional CFD analysis to evaluate a DAWT composed of a NACA 0015 airfoil on an ideal turbine, concluding that the power coefficient for a shrouded turbine is proportional to the mass flow, and the increasing flow through the rotor induced by the diffuser increases the extracted power for the same thrust coefficient compared to a bare wind turbine.

Wang et al. [6] measured the influence of a flanged diffuser on a shrouded wind turbine. Their experimental results revealed that the rotational speed and the dynamic strain of the blade are much higher than those without a flanged diffuser. Abe and Ohya [7] combined a numerical and experimental investigation of flanged DAWTs. They suggested that the loading coefficient for the best performance of a flanged diffuser is considerably smaller than for a bare wind turbine. In addition, it was necessary to avoid boundary-layer separation and maintain a high pressure-recovery

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**Nomenclature**

*Latin symbols*

| | |
|---|---|
| $a, a'$ | axial and tangential induction factors at the rotor |
| $a_{opt}$ | optimum axial induction factor |
| $A, A_3$ | area of the disc and the cross section at the diffuser outlet |
| $B$ | number of blades |
| $c$ | chord (m) |
| $C_D$ | drag coefficient |
| $C_L$ | lift coefficient |
| $C_M$ | torque coefficient |
| $C_n$ | normal force coefficient |
| $c_{p3}$ | pressure coefficient at the diffuser outlet |
| $C_P$ | power coefficient |
| $C_{Popt}$ | optimum power coefficient |
| $C_t$ | tangential force coefficient |
| $C_T$ | thrust coefficient |
| $dA$ | elementary area ($m^2$) |
| $dM$ | elementary torque (N m) |
| $dP$ | elementary power (W) |
| $dT$ | local thrust (N) |
| $F$ | Prandtl tip-loss factor |
| $p_0$ | pressure in the external flow (Pa) |
| $p_2$ | pressure at the turbine upstream (Pa) |
| $p_3$ | pressure at the diffuser outlet (Pa) |
| $P$ | output power (W) |
| $Pc$ | pitch of the vortex sheets (m) |
| $r$ | radial position at the rotor plane (m) |
| $R$ | radius of the rotor (m) |
| $s$ | spacing between the lamina (m) |
| $u$ | axial velocity at the rotor plane, $u = V_1 = V_2$ (m/s) |
| $u_1$ | axial velocity in the wake, $u_1 = V_4$, (m/s) |
| $v'$ | velocity of the external stream, $v' = \gamma V_0$ |
| $V_0$ | freestream wind velocity (m/s) |
| $V_3$ | axial velocity at the diffuser outlet (m/s) |
| $w$ | total induced velocity (m/s) |
| $W$ | relative velocity (m/s) |
| $x$ | local-speed ratio |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | angle of attack (rad) |
| $\beta$ | area ratio |
| $\gamma$ | diffuser velocity ratio |
| $\varepsilon$ | velocity ratio |
| $\eta_d$ | diffuser efficiency |
| $\theta$ | twist angle (rad) |
| $\lambda$ | tip-speed ratio |
| $\rho$ | density of the fluid ($kg/m^3$) |
| $\sigma$ | solidity of the turbine |
| $\phi$ | flow angle (rad) |
| $\Omega$ | angular speed of the turbine (rad/s) |

coefficient, to give high performance. Ohya and Karasudani [8] developed a turbine within a diffuser shroud with a broad-ring brim at the exit. The shrouded wind turbine power was increased by a factor between 2 and 5 over a bare wind turbine with the same blade diameter and wind speed. This was because a low-pressure region, due to a strong vortex formation behind the broad brim, draws more mass flow through the blades. These aspects highlight the importance of the development of models capable of optimizing DAWTs [9]. Although there are several works available in the current literature on DAWTs, the authors are unaware of any study of blade optimization with a diffuser.

Rio Vaz et al. [10] suggested that the optimum design of a DAWT might be achieved through three different approaches. The first one uses classical BET, which models the energy conversion by the torque generated on the blade elements, as demonstrated by Glauert [11]. Fletcher [12] applied this analysis to DAWTs, including wake rotation and blade Reynolds number effects. Igra [13] compared BET with data obtained from a shrouded wind turbine with a rotor diameter of 3 m and exit-area ratio of 1.6, producing 0.75 kW at 5 m/s with a power augmentation ratio (over the bare turbine) of 2.4.

The second approach is based on vortex theory, where each of the rotor blades is replaced by a lifting line and a vortex sheet is continuously shed from the trailing edge, as further described by Okulov and Sørensen [14]. The bound vorticity produces the local lift on the blades while the trailing vortices induce the velocity field in the rotor plane and in the wake. A recent example of this approach, Wood [15], determined the maximum performance of a bare turbine at low tip-speed ratio. Bontempo and Manna [16] used a single ring vortex to analyze the flow around a ducted actuator disk, in order to describe the flow around DAWTs.

The last methodology is CFD, e.g., Nobile et al. [17]. They undertook a computationally-expensive simulation of an augmented vertical axis wind turbine. CFD can be also coupled with optimization methods using genetic algorithms and evolutionary computation [18]. Global optimization using CFD can be very time-consuming, e.g. [19], and suggests the use of alternative optimization procedures, mainly those with cheaply computed objective functions. The present paper describes such a method, based on BET and the semi-empirical approach described by Rio Vaz et al. [2], where the conditions to extend the BET for the diffuser were detailed. In further support of this approach, it is noted that BET generally agrees well with experimental data [13]. In this paper the geometry of the rotor is determined using a one-dimensional analysis, assuming that, as for bare turbines, the gauge pressure in the far-wake is zero. This hypothesis aims at developing a theory having the closest equivalence to the momentum relations for bare turbines, as described, for example, by van Bussel [20]. In order to evaluate the proposed approach, comparisons with the classical Glauert optimization [11] and experimental results available in the literature were made.

The remainder of this paper is organized as follows. The next section introduces the simple one-dimensional axial momentum theory with a diffuser, showing the expressions for the maximization of DAWT power coefficient. Section 3 provides a detailed explanation of BET and its extension to DAWT. Section 4, shows the proposed optimization, and depicts the relationship for the optimum axial induction factor as a function of the diffuser speed-up ratio. Results and discussion are stated in Section 5, where the optimum conditions proposed for DAWTs are presented. Section 6 shows the conclusions of this study.

## 2. Axial momentum theory with diffuser

Simple momentum theory considers the air frictionless and ignores the rotational velocity component [2]. To model a diffuser with losses, an approach similar to that used to determine duct flow in the presence of losses [12,21] is developed. Fig. 1 shows the control volume for an ideal DAWT.