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Actuator Line Model for Diffuser Augmented Small Horizontal Turbines

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Abstract. *Diffuser-augmented turbines are an effective way of increasing power output in horizontal turbines. By surrounding the rotor with a diffuser, the incoming flow is accelerated, increasing the effective area over which the flow acts on the rotor blades. To further optimize the performance of these turbines, it is crucial to design the diffuser shape that generates the maximum power coefficient. However, current methods for diffuser optimization can be costly in terms of materials and time for evaluation. To address this issue, we propose a cost-effective approach using the Actuator Line Method. The methodology evaluates the turbine and diffuser as aerodynamic source forces over the flow, allowing the use of pure hex-core meshes since there is no real geometry. By leveraging actuator lines to model the diffuser and the turbine, our approach can achieve an improved convergence and the required accuracy in its computations at a significantly lower cost. Our research provides a comprehensive evaluation of the Actuator Line Method applied to diffuser-augmented turbines. It analyzes the performance of the S1223 profile for the diffuser, and the Hydro-K rotor, which are extensively studied geometries in the field. The lift and drag input data for these profiles have been obtained through basic panel methodology. Our study assesses the computational efficiency of the adjusted Actuator Line Method and its accuracy in predicting the power coefficient. To validate the methodology, we compare the numerical results of the actuator line method with full-geometry three-dimensional numerical analysis and wind tunnel tests from previous works. Results indicate that employing the Actuator Line Method on diffuser-augmented turbines reduces the computational time to less than 1% when compared to fully resolved geometries. Due to this efficiency, when coupled with the Blade Element Momentum methodology, this model can be used to design turbines along with their diffusers, leading to increased synergy and power output. The methodology accurately predicts the power coefficient at the diffuser-augmented turbine's operational point. However, at high tip-speed ratios, it overestimates the power output due to the Blade Element Momentum formulation's assumptions, which results in an imprecise near-wake description. Our research shows a promising approach for optimizing the diffuser shape for diffuser-augmented turbines, increasing power output and cost-effectiveness. Further studies are required to explore the Actuator Line Method's potential for diffuser-augmented turbines in more complex flow conditions.*

Keywords: *Actuator Line Method, Diffuser-Augmented Turbines, Computational Fluid Dynamics, Wind Tunnel Experiments, Small Horizontal Turbines*

1. Introduction

Diffusers are shrouding components of horizontal turbines that are able to increase its power output significantly. Diffuser-augmented turbines have a power output that is 20 to 50% higher than its bare turbine counterparts (Nunes *et al.*, 2020). As illustrated in Figure 1, diffusers expand the flow downstream, causing a pressure drop, that increases the flow upstream that passes through the turbine. Their drawback is the increased manufacturing cost and added complexity for the equipment, making their use not ideal for every situation. However, in the case of small hydro turbines, diffusers are a great choice to be implemented. In this situation there is already a need for a structure surrounding the rotor for the fixation of buoys and anchors. Furthermore, the costs of increasing the rotor diameter are more significant in comparison to the diffuser due to the camber of the rotor blades and its large chord per diameter ratio (Nunes *et al.*, 2019).

One of the research branches in diffuser-augmented turbines is the optimization of the diffuser shape in order to generate the maximum power coefficient for the turbine. The usual design methodology for turbines following the blade element momentum (BEM) is not capable of evaluating the effect of the diffuser. The diffuser effectively changes the flow distribution on the rotor, making the BEM predictions of the turbine's induction factor incorrect. Current design methodologies of diffuser-augmented turbines are based on heuristic testing using experimental models and numerical

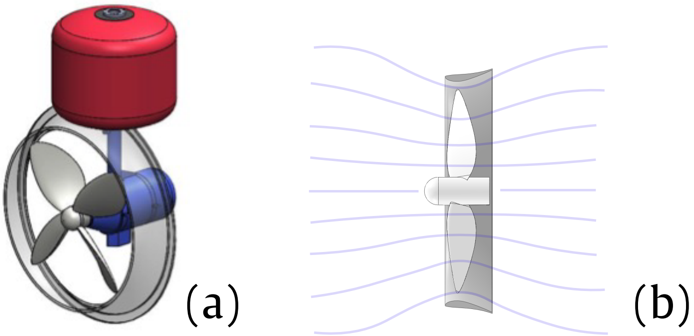

Figure 1: Example of diffuser-augmented turbine. Isometric view in (a) and cross-section view of rotor and diffuser in (b) with blue details to flow streamlines behavior.

analysis of fully resolved geometries (Ohya and Karasudani, 2010; Nasution and Purwanto, 2011). Both are are costly approaches regarding materials and time for the evaluation.

Specifically for diffuser augmented turbines, the computational cost is much higher than testing a bare turbine. As seen in Figure 2, the gap between the diffuser and the blade tip requires a fine refinement to capture the flow gradients in the region. Additionally, this corresponds to a region of higher flow speed, requiring an even smaller time step for the analysis. Both those factors decrease the feasibility of diffuser optimization using a fully resolved analysis.

Current research and optimization of diffuser augmented turbines work by using optimization algorithms (genetic, particle-swarm optimization, and random trees are the most popular) to test parameterized diffuser shapes (Khamlaj and Rumpfkeil, 2018; Oka *et al.*, 2015). They perform bi-dimensional analysis and optimize for the greatest lift disregarding the turbine. Since there is no turbine, this methodology disregards the interactions between the blade tip and the diffuser surface, and also does not take into account the flow distribution changes along the blades.

The current work proposes the implementation of the actuator line method for diffuser augmented turbines. The actuator line method is widely used for bare turbines, especially when studying wind farms, where wake interaction between the turbines is crucial. The actuator line method is a cost-effective alternative to compute the local flow speed and turbulence into the power output of a downstream turbine.

The actuator line method implements what can be called a "virtual" turbine. Instead of resolving the turbine geometry and the flow interactions with its surface at the boundary layer, the rotor is modeled as source forces applied to the flow. The actuator line model can produce accurate results about the flow field and power coefficient, in line with blade element momentum, for different flow conditions (Sørensen and Shen, 2002; Shen *et al.*, 2012; Ivanell *et al.*, 2009). It also accurately predicts wake interactions, and the influence of a turbulent flow field on the turbines' operation (Troldborg *et al.*, 2010; Yang *et al.*, 2015; Stevens *et al.*, 2018).

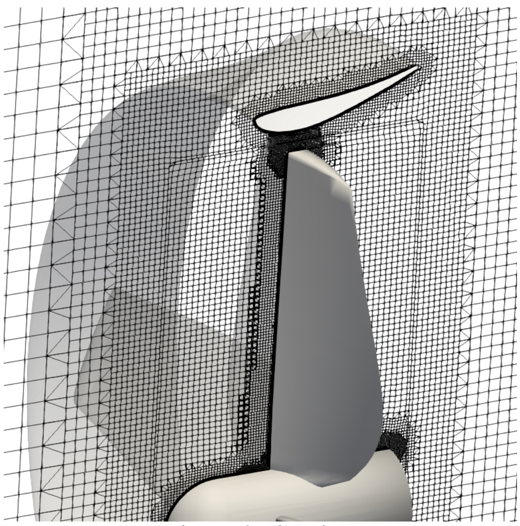

Figure 2: Caption

The actuator line method splits each blade of the rotor into several airfoil sections, illustrated in Figure 3(a). On each of those sections, the lift and drag forces,

$$f_L = \frac{1}{2} C_L(\alpha) \rho U_{rel}^2 c \tag{1}$$

and

$$f_D = \frac{1}{2} C_D(\alpha) \rho U_{rel}^2 c \tag{2}$$

are calculated for the given relative velocity at the section based on the input lift and drag coefficients. In Equations (1) and (2), C_L and C_D stands for the lift and drag coefficients, α for the airfoil attack angle, ρ for the flow density, and c for the airfoil section chord. The source forces are applied at the points illustrated in Figure 3(b). The actuating lines represent each blade rotating around the central axis at the chosen tip-speed ratio.

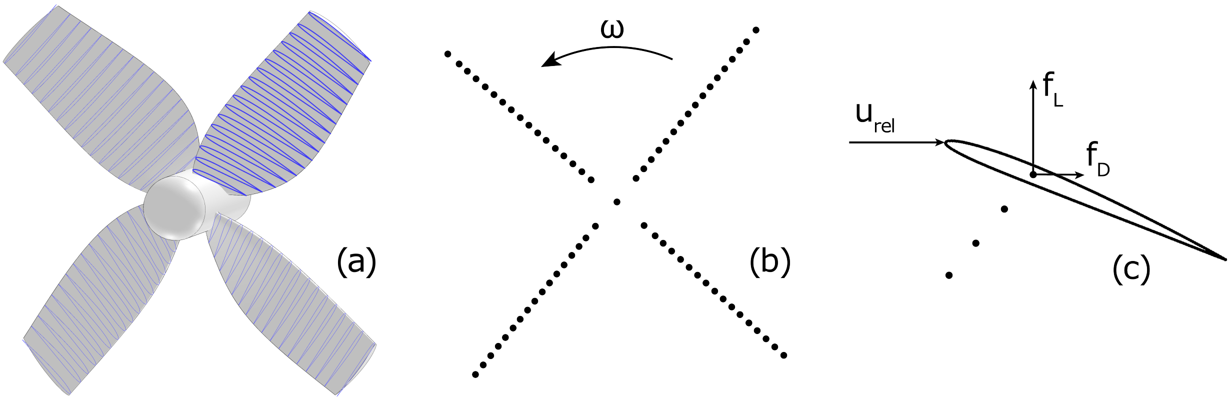

Figure 3: Actuator Line Model rotor simplification based on source forces. Blade sections in (a), source force points representing the blades in (b), and forces diagram for each source point in (c).

A diffuser-augmented turbine can be calculated and implemented to the method in a similar manner, as illustrated in figure 4. The diffuser shape is controlled by the opening angle, α, and the profile chord. Differently from the rotor, the diffuser does not rotate with time, it applies a static force to the flow, similarly to a tower. The lift generated from the airfoil profiles of the diffuser induce the increased mass flow that passes through the turbine.

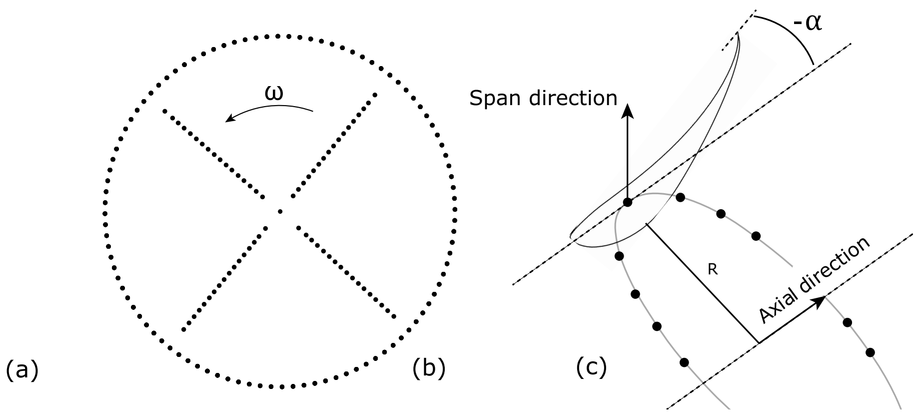

Figure 4: Diffuser implementation on Actuator Line Method. Source points illustrations in (a). Diffuser parameterization in (b).

The current work aims implement the actuator line method to diffuser-augmented turbines and to evaluate if it is capable of predicting the behavior of such turbines in terms of power coefficient, defined as

$$C_p = \frac{P}{0.5\rho U^3 A}, \tag{3}$$

where A refers to the rotor spanning area, U is the freestream velocity, and P is the power generated by the rotor. In the case of actuator lines,

$$P = \tau\omega, \tag{4}$$

where ω in the turbine rotational speed, and τ is the torque generated by the turbine, calculated using the source forces of each actuator point and their distance to the rotating axis.

2. Methodology

All the numerical analyses were performed in OpenFOAM, an open source software for computational fluid dynamics analysis—OpenFOAM Foundation (2021). The essential information about the numerical setup will be discussed in Sections 2.1 through 2.3. The detailed registry of all files for replication of procedures is stored at a public repository (Nunes, 2022).

2.1 Geometry

The Hydro-K geometry, with a diameter of 2.2 m, presented in Figure 5, is the reference for the rotor profile, twist, chord, and radius data. The diffuser shrouding the turbine follows the S1223 high-lift profile, a previously studied profile for diffuser-augmented turbines (Aranake *et al.*, 2015). The lift and drag polar curves have been obtained through the basic panel method. A previous work with the same turbine geometry provides the relevant experimental data for comparison regarding its power coefficient with and without a diffuser Nunes *et al.* (2019).

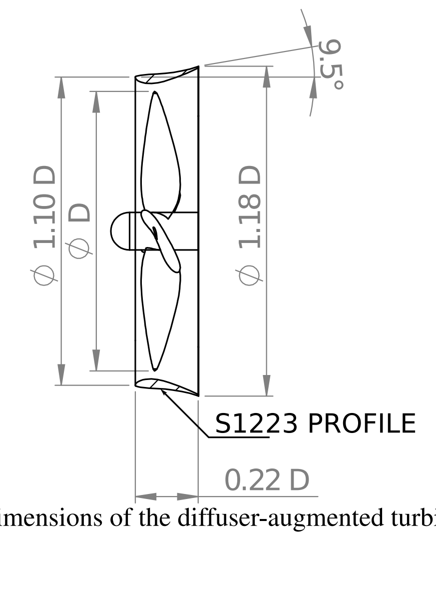

Figure 5: Dimensions of the diffuser-augmented turbine analyzed.

2.2 Boundary Conditions

The analysis domain is illustrated in Figure 6. The walls are far enough to guarantee uniform pressure and velocity fields at the boundaries. The flow speed was set to 10 m/s, and air at 25 °C was chosen as the immersed fluid. The origin is centered at the rotor, and gravity pulls at -$\hat{z}$ direction with 9.81 m/s^2. The turbulence intensity at the inlet is set to 0.5%, following the wind tunnel inlet conditions in which the reference experiments were performed (Nunes *et al.*, 2019). The turbine operates at a Reynolds of approximately 2 x 10^6.

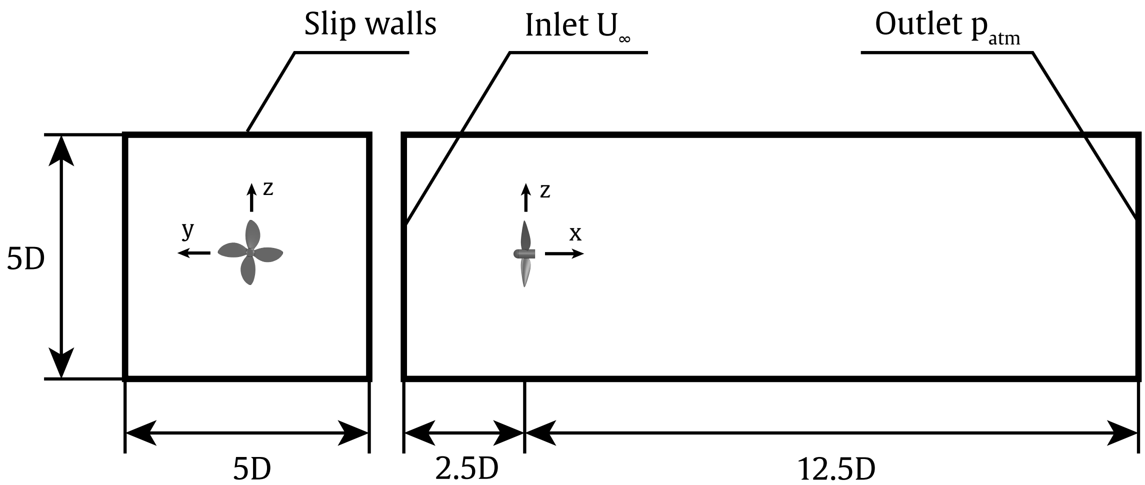

Figure 6: Numerical analysis domain of horizontal turbine. Frontal view on the left and side view on the right.

2.3 Modeling

The Actuator Line Model outputs the acting forces on the flow at each time step. Because of that, it is necessary to make an Unsteady RANS (Reynolds Averaged Navier-Stokes) evaluation of the case, even if, at first, we are only interested in a power coefficient analysis. The pressure-velocity coupling algorithm used was the Pressure Implicit Method for Pressure-Linked Equations (PIMPLE). It is a combination of the PISO (Pressure-Implicit with Splitting of Operators) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithms. It is designed to solve transient, incompressible flow problems, especially when the time-steps are not too small, and hence the flow can be seen as pseudo-steady for each time-step. This solver reduces the number of loops required to converge the momentum predictor matrix as long as the time step is sufficiently small. A single outer loop with two inner loops has been employed, along with a tolerance of 1e-6 on all relevant fields.

The turbine is simulated as acting forces. Its actual geometry is not included in the domain. Therefore, no near-wall calculations take place at the turbine. The Reynolds Stress Tensor only needs to be computed for the log-law region. For the reasons stated above, the $k-\epsilon$ is the chosen eddy viscosity model to decrease the computational cost involved in each iteration. The mean chord, with 0.34 m, is the reference length scale for the turbulence dissipation rate.

2.4 Computational Environment

The central processing unit (CPU) of the system was an Intel(R) Core(TM) i7-2600 operating at a clock speed of 3.40GHz, with a total of 8 cores/threads. In terms of memory, the system was equipped with a total of 15GiB RAM of DDR3 type. This computational setup ran on the Ubuntu 20.04 operating system, codenamed "Focal." For the parallel processing aspect of the simulations, the *mpirun* tool was employed. This was implemented across a cluster comprising four computers, each mirroring the specifications detailed above, culminating in the use of 32 cores in total for the analysis. Each case, whether for the mesh study or power coefficient analysis, was assigned to an individual core for serial execution. This arrangement ensured that each machine processed eight cases in parallel at any given moment. This distribution of processes reduced the computational time due to the serialization of the solution.

2.5 Mesh Study

"The grid resolution near the wall does not resolve the boundary layer completely, but because the rotor is far from the walls, we believe the effect of not resolving this boundary layer is negligible."

The relevant parameter of the study is the power coefficient of the turbine evaluated at the operative point, a tip-speed ratio of 1.64. Since the domain has a square profile and no inner geometry walls, the created mesh is a structured cuboid mesh.

Two relevant areas were considered for mesh refinement, illustrated in Figure 7. The turbine zone is responsible for the accuracy of the velocity inputs for each actuator blade element, illustrated in Figure 3. The wake zone is responsible for the accuracy of the pressure field that affects the flow upstream of the turbine. Notice, however, that the refined wake zone only extends two diameters behind the turbine. This distance is where the most important fluctuations that affect the power coefficient occur.

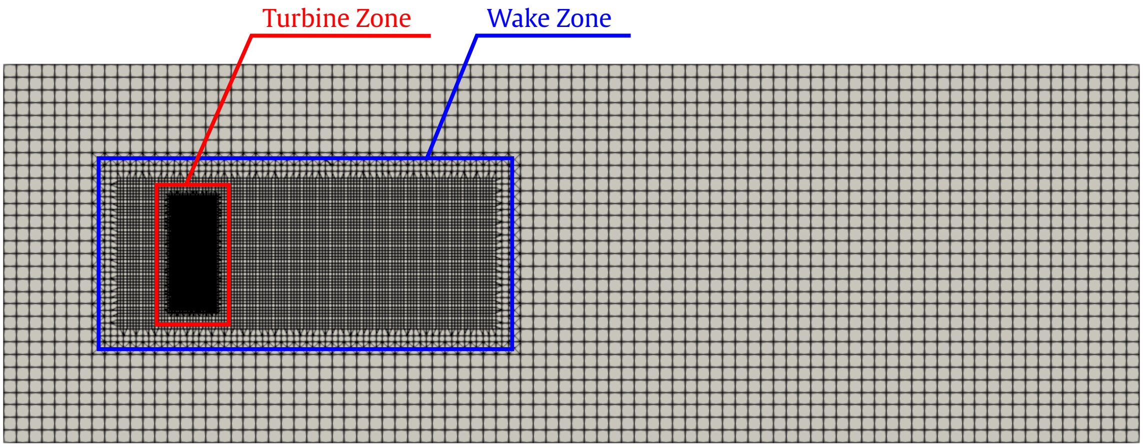

Figure 7: Structured mesh for numerical analysis of single turbine using the Actuator Line Model. Detail to refinement areas of study.

The refinement of the relevant areas, turbine and wake, is performed using the bisection method. It splits the mesh elements in half to maintain the mesh structure. The turbine zone takes refinement priority since it is inside the wake zone. Figure 8 shows the turbine's power coefficient behavior as the turbine zone refinement takes place. The mesh was considered converged when the variance of its power coefficient converged with a tolerance of 1%.

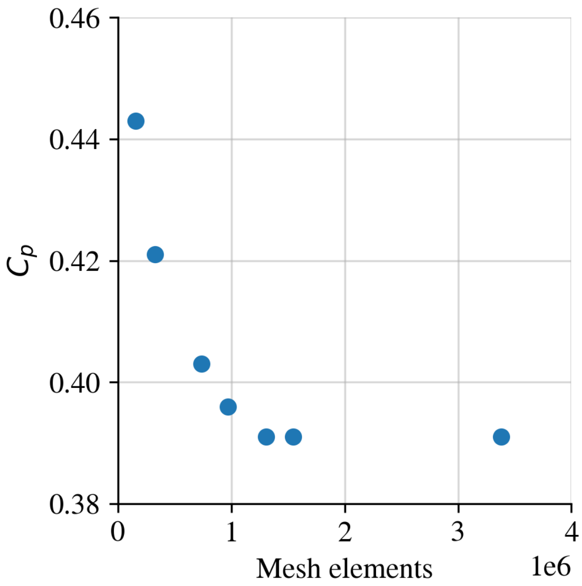

Figure 8: Influence of turbine zone refinement referred in Figure 7. Convergence of power coefficient using the Actuator Line Model for the Hydro-K turbine.

According with Figure 3, each turbine blade was split into 50 sections, each with a width of 0.02 D. The mesh refinement on the turbine zone shows convergence at an element size of 0.0104 D. The resulting power coefficient is not sensitive to refinements in the wake zone as in the turbine zone, the power coefficient remains stable as long as the turbine zone maintains a fine mesh.

The wake zone requires less refinement because it is responsible for the mean inflow speed distribution upstream. The turbine zone, however, requires as much refinement as there are blade sections. It is responsible for the specific values of relative velocity captured by each blade section.

The final chosen mesh contains 1.3 x 10^6 elements with an element size of 0.0104 D at the turbine zone, 0.0833 D at the wake zone, and 0.1666 D outside. This case was validated against experimental and numerical results of the same turbine and shown in Table 1.

Table 1: Power coefficient validation of Actuator Line Model Numerical Analysis for Hydro-K turbine.

Reference	Type	C_p	Mesh elements
Mendes (2020)	Full geometry CFD	0.383	5.5 x 10^6
Mendes (2020)	Experimental model	0.416	-
Macias (2016)	Full geometry CFD	0.390	5.5 x 10^6
Macias *et al.* (2020)	Actuator Line Model	0.401	4.4 x 10^6
Current	Actuator Line Model	0.395	1.3 x 10^6

3. Results and Discussions

Although the current implementation of the actuator line model on the Hydro-K turbine has shown similar results to the previous modeling performed Macias *et al.* (2020), there is still room for improvement. The power coefficient curve, shown in Figure 9, overestimates the power coefficient at high tip-speed-ratios. That was expected to a certain extent since the model is based on BEM. However, an overshoot much larger than the BEM method signifies there is still something unrelated to the aerodynamic forces on the blades not being properly modeled. Although the actuator line method reproduces accurately the velocity and turbulence fields, similar behavior has been reported by Bachant (2018) regarding the power coefficient, pointing to the force distribution over the actuator points and velocity sampling as improvement avenues. This behavior and warrants further mesh study specifically for high tip-speed ratios. Moreover, due to the propeller-like nature of the turbine, the influence of the solidity of the rotor on the profile forces is not insignificant, skewing the induction factor for high tip-speed ratios. The Buhl-Glauert correction, applied to the BEM method for high tip-speed ratios should be considered. However, even without the correction, the BEM method more accurately predicts the power coefficient. Furthermore, the re-circulation phenomena it tries to account for should be something that is inherently evaluated when solving the flow with actuating forces.

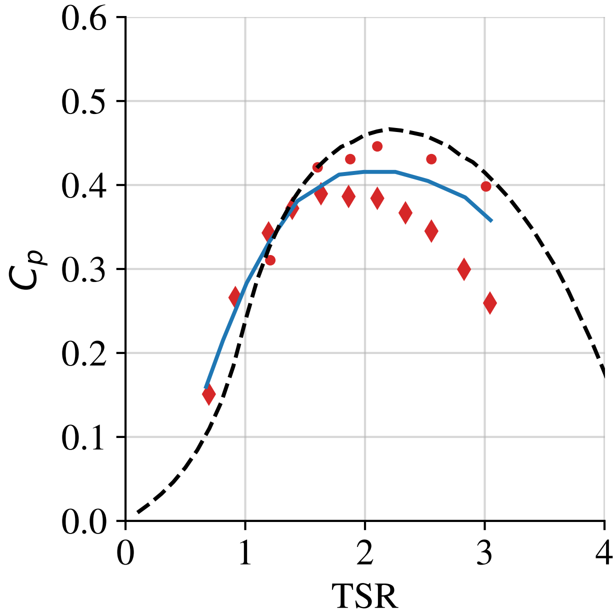

Figure 9: Power coefficient analysis for ALM model of bare turbines. (◆) Full geometry CFD from Macias *et al.* (2020). (——) Blade element momentum method. (●) Actuator Line Model from Macias *et al.* (2020). (- - -) Current Actuator Line Model.

The diffuser augmented turbine, in Figure 10, presents similar behavior. The over-prediction in this case stems once again from the bare turbine, as the diffuser has negligible variation in its lift forces due to changes in tip-speed ratio. Even at the turbine operation point, the diffuser-augmented turbine fails at predicting the power coefficient accurately.

Despite its shortcomings, when comparing the actuator line model with the fully resolved geometry analysis, the actuator line method for diffuser-augmented turbines reduces the total computational time from 9210 to 49 core-hours. It allows a design optimization study to be performed two-hundred times faster as an initial guess. The results can later be validated using more accurate models.

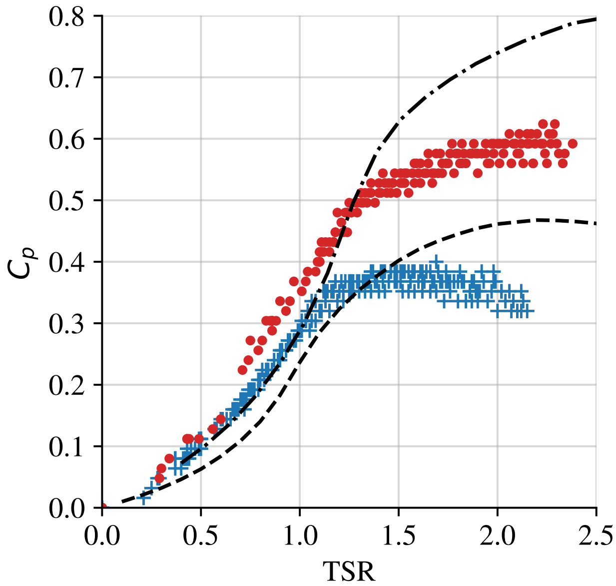

Figure 10: Power coefficient analysis for ALM model of diffuser-augmented turbines. (+) Experimental data for bare turbine from Nunes *et al.* (2019). (•) Experimental data for diffuser-augmented turbine from Nunes *et al.* (2019). (- - -) Actuator line method for bare turbine. (- · -) Actuator line method for diffuser-augmented turbine.

4. Conclusions

Diffuser-augmented turbines are capable of achieving a higher power compared to bare turbines at an increased structural cost and complexity. Research in the past years focuses on optimizing diffuser shape, but the traditional design methodology is insufficient, necessitating costly experimental and numerical analyses. The computational cost of fully resolving diffuser augmented turbines is high due to the need for fine mesh refinement at the gap and smaller time steps. Existing research utilizes optimization algorithms but overlooks important blade-diffuser interactions and flow distribution changes. To address these challenges, the proposed work implements the actuator line method, commonly used for bare turbines, to model the diffuser-augmented turbine. The method divides each blade into sections, calculating lift and drag forces to generate source forces applied to the flow. The proposed work implements this method for diffuser augmented turbines and evaluate its accuracy in predicting power coefficient.

The numerical analysis is performed using OpenFOAM for studying diffuser-augmented turbines. The geometry of the Hydro-K turbine with a diameter of 2.2 m is used as a reference, and the diffuser follows the S1223 high-lift profile. Experimental data from previous work is used for comparison.

The implementation of the actuator line model on the Hydro-K turbine shows similar results to previous modeling efforts but exhibits room for improvement. The power coefficient curve overestimates the power at high tip-speed ratios, indicating a discrepancy between the modeled aerodynamic forces on the blades and the actual behavior. This suggests a need for further refinement in the force distribution over the actuator points and velocity sampling. A mesh study specifically targeting high tip-speed ratios is recommended. Additionally, considering the propeller-like nature of the turbine, the influence of rotor solidity on the profile forces and the application of the Buhl-Glauert correction for high tip-speed ratios should be explored. The diffuser-augmented turbine also faces challenges in accurately predicting the power coefficient, with the over-prediction primarily stemming from the bare turbine rather than the diffuser itself. However, despite its shortcomings, the actuator line method for diffuser-augmented turbines reduces the total computational time from 9210 to 49 core-hours in comparison with fully resolving the three dimensional geometry.

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