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OPTIMAL PERFORMANCE OF A SAVONIUS TURBINE USING AN OBSTACLE SHIELDING THE RETURNING BLADE

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ABSTRACT

Due to the worldwide energy crisis, research and development activities in the field of renewable energy have been considerably increased in many countries. In Germany, wind energy is becoming particularly important. Although a considerable progress has already been achieved, the available technical design is not yet adequate to develop reliable wind energy converters for conditions corresponding to low wind speeds and urban areas. The Savonius turbine appears to be particularly promising for such conditions, but suffers from a poor efficiency. The present study considers an improved design in order to increase the output power and the static torque of the classical Savonius turbine, thus obtaining a higher efficiency and better self-starting capability. To achieve these objectives and quantify the available increase in performance, the position of an obstacle shielding the returning blade of a Savonius turbine and possibly guiding the wind toward the advancing blade is optimized to obtain the best possible performance. This automatic optimization is carried out by coupling an in-house optimization library (OPAL) with an industrial flow simulation code (ANSYS-Fluent), as documented for example in [1]. The optimization process takes into account both output power coefficient and static torque as target functions, considers the position and the angle of the shield as optimization parameters, and relies on Evolutionary Algorithms. A considerable improvement of the Savonius turbine performance can be obtained in this manner.

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KEYWORDS

Savonius rotor, Wind energy conversion, Optimization, Evolutionary Algorithms, Turbomachines.

Introduction

Wind energy is one of the most promising source of renewable energy. It is pollution-free, abundantly available in the earth's atmosphere, available locally, and can help in reducing the dependency on fossil fuels. Many developed and developing countries have realized the importance of wind as an important resource for power generation and necessary measures are being taken up across the globe to tap this energy for its effective utilization in power production.

According to the results released by the Global Wind Energy Council (GWEC), wind energy developing countries (more than 70) have taken the net wind energy installed capacity to a record high exceeding 742 GW. Despite constraints facing supply chains for wind turbines, the annual market for wind energy continues to increase at a staggering rate higher than 30%. It has been estimated that roughly 10 million MW of energy are continuously available in the earth's wind. Greenpeace predicted that about 10% electricity could be supplied by the wind in 2020 using improved technology; experts predict that wind power would capture 5% of the world energy market by the year 2020 [2].

The Savonius Turbine

S.J. Savonius initially developed the vertical axis Savonius rotor in the late 1920s. The concept of the Savonius rotor is based on cutting a cylinder into two halves along the central plane and then moving the two half cylinders sideways along the cutting plane, so that the cross-section resembles the letter S (fig. 1, [2]).

The Savonius rotor, which is a slow-running vertical axis wind machine ($\lambda \simeq 1.0$) has a rather poor efficiency : $C_p \simeq 0.2$ at best. Nevertheless, it can present some advantages for specific applications, in particular due to its simplicity, resulting robustness and low costs.

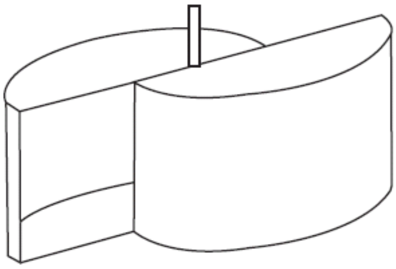

Figure 1. Savonius rotor [2]

Performance of a Savonius Turbine

Using the notations of Fig. 2, the velocity coefficient is defined as:

$$\lambda = \omega R / U \tag{1}$$

For a Savonius rotor of height H, a wind of incoming velocity U, the mechanical power P and the mechanical torque on the axis of a Savonius turbine can respectively be written as follows:

$$C_p = \frac{P}{\rho R H U^3} \tag{2}$$

and

$$C_m = \frac{M}{\rho R^2 H U^2} \tag{3}$$

where C_p and C_m are respectively the power coefficient and the torque coefficient. In the following sections, a rotor is called a *conventional Savonius rotor* if the geometrical parameters a and e are respectively equal to 0 and $d/6$. This reference configuration of the rotor has been extensively studied (see citations in [3]). Values of C_p and C_m have been experimentally determined as a function of the velocity coefficient λ for this conventional configuration, allowing a direct estimation of mechanical power and mechanical torque.

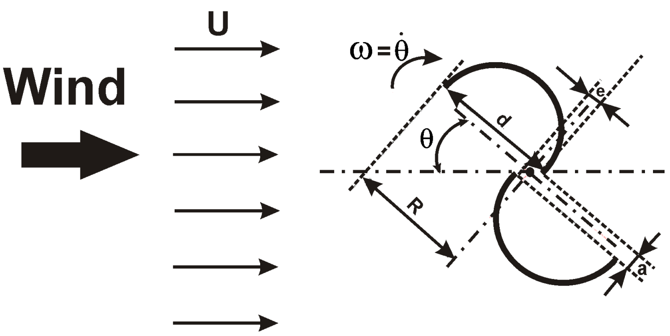

Figure 2. Schematic description and main parameters characterizing a Savonius rotor

Purpose of the Present Work

The previous theoretical and experimental results illustrate the main drawback of the Savonius turbine: its poor efficiency [4, 5]. Therefore, many designs have been proposed in the literature to improve the performance of this turbine (see e.g. [3, 6–10]). In Table 1 a summary of the most important modification proposals are listed.

In the present study we will investigate numerically the effect of an obstacle shielding partly the returning blade of a Savonius turbine. This should reduce the reverse moment, and as a consequence the total moment of the turbine will be increased, since the total moment is the moment difference between the advancing and the returning blade. More specifically, the position and the angle of the obstacle relative to the returning blade will be optimized. All parameters describing the obstacle position are listed in Fig.3.

Optimization

The mathematical optimization of turbomachines is still a relatively new field or research (for a recent overview, see [11]). Optimization is used here to identify the best position and angle of the obstacle shielding the returning blade, in order to maximize the performance of the Savonius turbine. Optimization criteria can be considered both for mechanical and for flow properties, as done in the present work. The central goal when designing an improved Savonius turbine is to achieve high efficiency and high power output. Furthermore, it must be kept in mind that turbomachines often operate outside the nominal (or design) conditions. Therefore, after optimizing the configuration for the maximum output power coefficient, known to occur for a speed ratio $\lambda \simeq 0.7$, the full range of speed ratios will be considered.

Optimization methods attempt to determine the n design variables $X_i (i = 1 \ldots n)$ that maximize a user-defined objective function, denoted $OF(U(X_i), X_i)$, where $U(X_i)$ is the solution of the flow equations obtained by Computational Fluid Dynamics (CFD) [1]. In the present paper, the free design variables considered for the optimization will describe the obstacle position. For this purpose, three parameters are considered (X_1, Y_1 and X_2), which together with a fixed value for Y_2 are sufficient to fix clearly the geometry of the obstacle (see Fig.3). The objective function considers only one output of the simulation, that should be maximized as far as possible: the output power coefficient C_p.

Optimization Methodology

Until recently, the denomination "optimization" was mostly used in the engineering literature to describe a trial-and-error, manual procedure at the difference of a real, mathematical optimization. This is now changing rapidly. In the present project, the optimal position and angle of the obstacle will rely on a mathematical optimization, as a first step toward a more aggressive optimization of all important parameters affecting the performance of the Savonius turbine.

An appropriate algorithm must be chosen. A considerable experience is available in our group concerning the mathematical optimization relying on CFD

Table 1. Improving the performance of Savonius turbine

Design	*Gain*	*Description*	*Comments*
Deflector Plate [6]	20%	Not proved in practice	No details since 1992
Twisted-blade [7]	$\simeq$ 27% relative	Complex design, cost?	Good self-starting capability
Guide-Box Tunnel [8]	50% (3 blades)	Complex design	
Modified Savonius [9]	60% in static torque	Not proved in practice	Vibration problem
Guide Vanes [10]	Depends on wind speed	Bad for large λ	Good stability

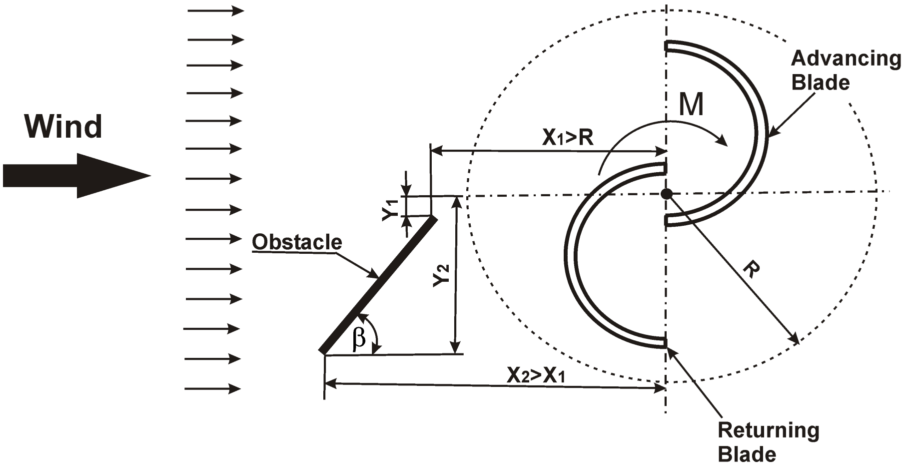

Figure 3. Schematic description and optimization parameters

evaluations [1]. We therefore employ our own optimization library, OPAL (for OPtimization ALgorithms), containing many different optimization techniques. OPAL has already been coupled in the past with different CFD solvers (in-house codes, ANSYS-Fluent, ANSYS-CFX) and has been employed successfully to improve a variety of applications, for example heat exchangers [12], turbomachines [13] or burners [14, 15].

For the present configuration, Evolutionary Algorithms are employed. The employed parameters are listed in Table 2.

A fully automatic optimization takes place, using OPAL (decision-maker for the configurations to investigate), the commercial tool Gambit for geometry and grid generation (including quality check) and the industrial CFD code ANSYS-Fluent to compute the flow field around the Savonius turbine. As a result of the CFD computation the output power coefficient is determined, and is stored in a result file. The procedure is automated using journal scripts (Gambit, Fluent) and a master program written in C, calling all codes in the right sequence. By checking the values stored in the result file, OPAL is able to decide how to modify the input parameters , before starting a new iteration. The fully coupled optimization procedure is a complex task, which has been described in detail in previous publications. We thus refer the interested reader to [1, 12, 14, 15] for a complete description of the procedure.

Table 2. Parameters of the Evolutionary Algorithm

Parameter	*Value*
Population size, N	20
Number of generations	13
Survival probability	50%
Average probability	33.3%
Crossover probability	16.7%
Mutation probability	100%
Mutation magnitude	30%[a] (i.e. ±15%)

[a] This value is multiplied by 0.8 at each generation. For example the mutation magnitude is only 4% (±2%) after 10 generations. Mutation magnitude must be decreased during the optimization process to stabilize the population.

Numerical Flow Simulations

From the literature it is known that an accurate CFD simulation of the flow around a Savonius turbine is a challenging task, mainly due to its highly time-dependent nature and to the fact that flow separation plays an important role for the efficiency of the system. It is therefore necessary to check the full numerical procedure with great care. Afterwards, the resulting methodology must be validated.

All flow simulations (denoted also CFD for Computational Fluid Dynamics) presented in this work rely on the industrial software ANSYS-Fluent. The unsteady Reynolds-Averaged Navier-Stokes equations are solved using the SIMPLE (Semi-Implicit Method for Pressure-linked Equations) algorithm for pressure-velocity coupling. The flow variables and all turbulent quantities are discretized in a Finite-Volume formulation using a second-order upwind scheme. In order to model turbulence, the realizable $k-\varepsilon$ model is employed, which is usually recommended for rotating bodies. For the present configuration, two-dimensional simulations are sufficient (no geometry change in the third direction when excluding boundary effects), so that very fine grids can be employed.

The unsteady flow is solved by using the Sliding Mesh Model (SMM). Three complete revolutions are always computed, using a constant time-step; the first one is used to initiate the correct flow solution, while the flow properties (in particular the power coefficient C_p and the torque coefficient C_m) are obtained by averaging the results during the last two revolutions. It has been checked that the results do not change noticeably by iterating further in time. On a standard PC, one evaluation (i.e. three revolutions for one specific configuration) takes about 280 minutes of computing time.

After setting up this general CFD model, a grid-independence study has been carried out. Corresponding results are shown in Fig.4. Several different two-dimensional grids of increasing density and quality, composed of 3400 up to 116000 cells, have been tested for the Savonius turbine with a deflecting plate (choosing $X_1/R = 1.4$, $Y_1/R = 0.24$ and $X_2/R = 1.76$ at $\lambda = 1.0$). It is easy to notice from Fig.4 that the five coarsest grids are associated with a large variation of the power coefficient. On the other hand, all remaining grids employing more than 71000 cells lead to a variation of the output quantity below 1.8%. Since the cost of a CFD evaluation obviously increases rapidly with the number of grid cells, the intermediate grid range between 75000 and 95000 cells has been retained for all further results shown in the present paper.

CFD Validation

After an acceptable grid has been identified, the full numerical model has been validated by comparison with published experimental results [10] for a conventional Savonius turbine. The results shown in Fig.5 demonstrate the excellent agreement obtained between CFD and experiments for this standard configuration, at least for $\lambda > 0.3$. Both the torque coefficient and the target function of the optimization to come (power output coefficient) are very well predicted. As a consequence, it is now possible to start the investigation and optimization of the Savonius tur-

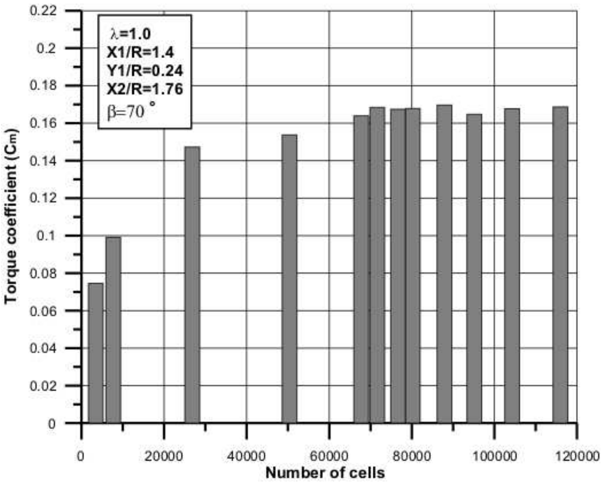

Figure 4. Grid-independence study for the torque coefficient

bine involving a deflecting plate.

Self-starting capability

One important issue associated with wind energy is the self-starting capability of the system. For decentral, low-cost applications as considered here, it is essential to obtain a self-starting system. To investigate this issue, the static torque exerted on a turbine at a fixed angle has been computed by CFD as a function of this angle θ. Figure 6 shows the obtained static torque coefficient obtained for three different positions of the deflecting plate as a function of θ. The experimental results of [10] (conventional turbine) are also shown for comparison. Due to periodicity, the results are only plotted for θ between 0 and 180°. These computations demonstrate that the deflecting obstacle has a considerable and positive effect on the static torque coefficient. The conventional turbine shows a very large variation of the static torque coefficient as a function of θ, with negative values around $\theta = 140^\circ - 170^\circ$ (no self-starting). For all investigated positions involving a deflecting obstacle (only 3 are shown in the figure, but many more have been computed), the negative torque region completely disappears, with a minimum value of C_{m_s} higher than 0.1. Apart from that, the evolution as a function of θ is similar to that of the conventional turbine. As a whole, employing a deflecting obstacle improves considerably the self-starting properties of the turbine, leading to self-starting capability at any angle, which is a major advantage.

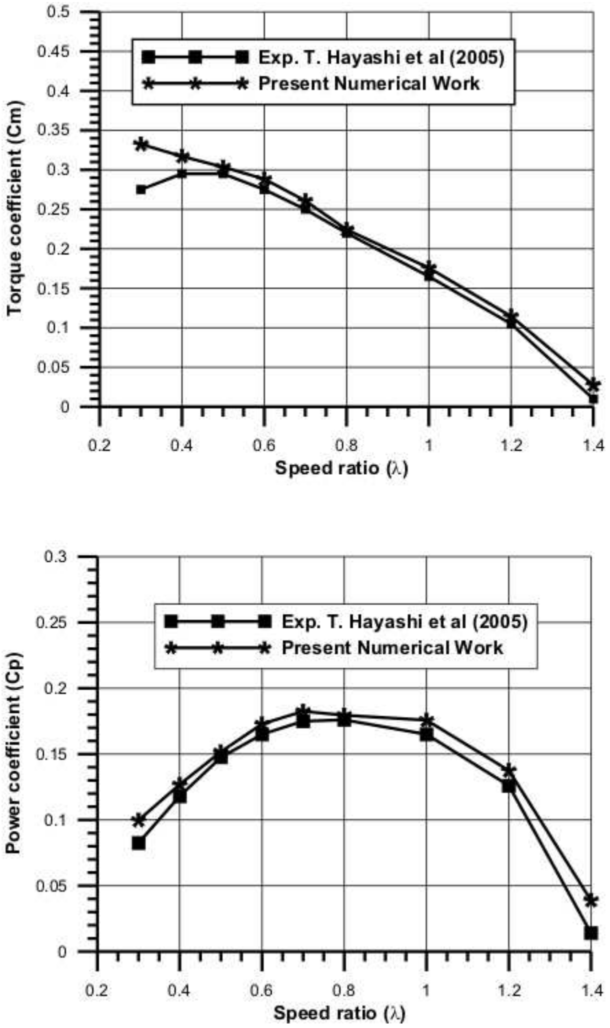

Figure 5. Validation of computational model, a: torque coefficient (top), b: power coefficient (bottom), compared to experimental results [10]

Optimization of deflecting obstacle position

Finally, the mathematical optimization procedure described previously (Evolutionary Algorithms relying on automated evaluations through CFD) is employed to find the optimal position of the deflecting plate. This is done for a speed ratio $\lambda = 0.7$, considering an incident wind velocity $U = 10$ m/s. This value

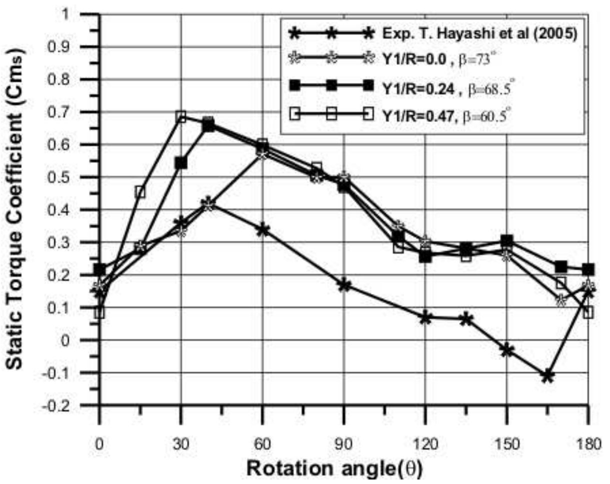

Figure 6. Static torque coefficient as a function of the angle θ for three different values of Y_1 choosing $X_1/R = 1.4$ and $X_2/R = 1.76$

of λ is retained, since it is known from the literature that it corresponds to the peak power coefficient of the conventional turbine.

Three degrees of freedom are left simultaneously to the OPAL optimizer: X_1, Y_1 define the upper tip of the deflecting obstacle; the value X_2 is sufficient to define the position of the lower tip, since Y_2 is taken constant, with $Y_2/R = 1.177$ (Fig.3). With these three factors, the position of the deflecting plate is perfectly determined, and the angle β can be computed as well.

In this first study, a relatively small domain has been defined for the optimization in the parameter space The limits of this domain for the three parameters are $(1.2 : 1.4)$ for (X_1/R), $(0 : 0.47)$ for (Y_1/R) and $(1.2 : 1.76)$ for (X_2/R). With these parameters, there is no possibility that the plate touches the turbine $(X_1 > R)$. Furthermore, the condition $X_2 > X_1$ is implemented in the optimization procedure. The corresponding positions of the deflecting plate lead to configurations shielding typically half of the returning blade. The angle β varies then between 50 and 90°.

Finally, the optimization process thus involves simultaneously three parameters (or degrees of freedom): X_1, Y_1 and X_2. For each geometrical configuration one single objective (power output coefficient) is determined by CFD evaluations, and should be maximized by the optimization procedure.

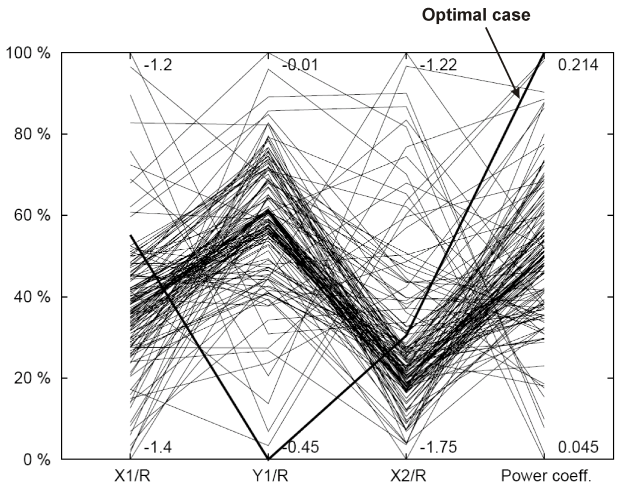

Figure 7. The three input parameters of the optimization and the power coefficient represented using parallel coordinates (the negative sign indicates to obstacle position at Cartesian coordinates)

The results presented in Fig.7 indicate that the considered objective is indeed considerably influenced by the three free parameters, X_1, Y_1 and X_2. As a whole, 140 different geometrical settings have been evaluated by CFD, requesting as a whole 27 days of computing time on a standard PC. Note that the user-waiting time could be nevertheless much shorter, if the CFD evaluations are carried out in parallel (see e.g. [1]).

An optimal configuration (highest point in the right column in Fig.7, shown with symbols) can thus readily be identified for $\lambda = 0.7$. This optimum point corresponds to the deflecting obstacle position $X_1/R = 1.29265$, $Y_1/R = 0.4412$ and $X_2/R = 1.58823$, which leads to an angle $\beta = 68.1°$. This optimal condition leads to a power coefficient $C_p = 0.214$ and a torque coefficient $C_m = 0.306$.

When compared with the standard Savonius turbine, the optimal point found by the optimization procedure corresponds simultaneously to an increase of the power coefficient by 0.032 and of the torque coefficient by 0.046 at $\lambda = 0.7$. For the power coefficient, this means a relative increase of the performance by 12.4% compared to the conventional Savonius turbine.

It is now important to check how this gain will change as a function of λ. Therefore, the performance of this configuration has been computed for the full range of useful λ-values, as shown in Fig.8. Again, the experimental results of [10] (conventional turbine) are also shown for comparison. Figure 8 demonstrates that the improvement of both torque coefficient and power output coefficient is observed throughout for all values of λ, compared to the conventional Savonius turbine. The absolute gain for C_p increases slightly with λ, the relative increase is highest for the largest values of λ.

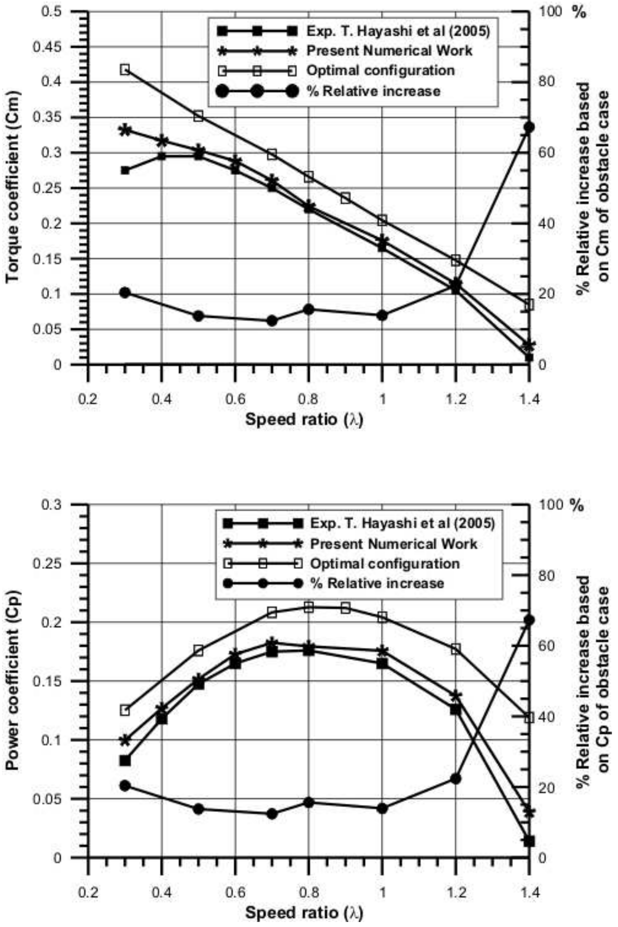

Figure 8. Performance of the optimized configuration compared to the conventional Savonius turbine, a: torque coefficient (top), b: power coefficient (bottom)

Conclusions

In this work accurate CFD simulations of the unsteady behavior or a conventional Savonius turbine have been carried out, after validating the numerical procedure against experimental measurements. The realizable $k-\varepsilon$ turbulence model can be employed for a quantitative analysis of the performance, provided a sufficiently fine grid is used. The Savonius turbine is a promising concept for small-scale wind-energy systems, but suffers from a poor efficiency. Therefore, the major objective of the present study is to identify an improved design, leading to higher values of the power coefficient and of the static torque of the Savonius turbine, thus obtaining a higher efficiency and better self-starting capability. For this purpose, a deflecting plate shielding partly the returning blade of a Savonius turbine and possibly redirecting the wind toward the advancing blade is introduced. The installation of the obstacle improves the self-starting capability for all configurations. While the conventional Savonius turbine shows negative values for the static moment in a range of angles, the deflecting plate leads to a positive static moment value at any angle.

Finally, the position of the deflecting plate has been optimized in a fully automatic manner, in order to obtain the best possible performance. The optimization relies on Evolutionary Algorithms, while all geometrical configurations are evaluated in an automatic manner by CFD. This optimization procedure is able to identify a considerably better configuration than the conventional Savonius turbine, leading in particular to a relative increase of efficiency by 12.4% at $\lambda = 0.7$. This gain is also observed for the torque coefficient, and is even higher for larger values of λ. Therefore, the overall effect of this deflecting plate is extremely positive.

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