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Research Article

Performance Analysis of The Concentrator -Wind Turbine Combination

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Abstract

Wind energy is a renewable energy resource that can be used to ensure energy sustainability without causing environmental pollution. In this content, many studies have been going on to acquire more energy from the wind. One of the approaches to get more energy from the wind turbine is to increase the wind speed at the wind turbine. In order to achieve this, concentrator is added around the turbine, so called the turbine-concentrator system. Concentrator creates a low-pressure zone behind and consequently increases wind speed at the wind turbine zone in the concentrator. The optimization analysis of the combinations of the wind turbine and concentrator leading to the maximum free wind speed increase is curried out. In the optimization analysis, the Response Surface Method with 2D CFD analysis is applied. Using optimum geometric parameters, the performance analysis of the wind turbine-concentrator combinations is determined by the 3D CFD analysis. It is seen that turbine performance can be significantly improved by using concentrator. Concentrator increases the wind speed and power output by a factor about 1.3 and 2.5 respectively. Thus, concentrator provides more power generation from the wind turbine and also can be used to generate energy in the region with poor wind statistics.

Introduction

Recently, in worldwide, scientific research and studies on renewable energy sources have increased and a huge research fund has been provided to researchers. It is known that the renewable energies make positive contribution to economic life and environment of countries. Also, renewable energy is able to be seen as an opportunity to reduce energy dependence on the fossil fuel exporting countries. Therefore, countries are focused on renewable energies, mainly on wind and solar energies.

Wind energy, which is a clean and renewable source of electricity, is an energy that can be easily and quickly converted into electrical energy in the world. Many studies have been going on to get more energy from the wind. One of the approaches to get more energy from the wind turbine is to increase the wind speed at the wind turbine. In order to achieve this, concentrator is added around the turbine, so called the turbine-concentrator system. Concentrator creates a low-pressure zone behind the turbine and consequently increases flow speed at the wind turbine zone in the concentrator.

There are some studies in the literature to icrease the output energy of the wind turbine. In the literature, there are some studies to find a mechanism to accelerate approaching flow to the wind turbine. A concentrator, can be used to increase the flow speed through the rotor and consequently capturing wind energy in a more efficient way [1,2]. In literature, there are two types of concentrator; one of this is flanged typed and the other is airfoil typed structure surrounding the rotor. A flanged type concentrator, as shown in Figure 1, generates a large separation region behind concentrator and consequently increases wind speed at the wind turbine zone [3].

Matsushima et al. [4] experimentally demonstrated that a wind turbine enclosed by a small-capacity flanged concentrator produces 2.4 times more energy than the turbine without flanged concentrator. Toshimitsu et al. [5] studied the performance of a wind turbine placed in a barrel with a flanged emitter using the Particle Image Velocity (PIV) technique and concluded that the wind power ratio was found to be about 2.6 times higher. Similar studies about flanged concentrator were carried out by different authors [6-9].

In the airfoil shaped concentrator, as shown in Figure 2, the mass flow rate increases through the rotor by the lift effect of airfoil [10,11]. Also adding a flap or slot behind the airfoil shaped concentrator, large concentrator exit area can be obtained without flow separation providing more mass flow rate inside the concentrator [12,13].

In all the works in the literature, they considered the concentrator without wind turbine and they gave the performance of the concentrator. As the wind turbine creates the blockage effect in the concentrator and consequently, the performances of the concentrator with and without turbine are not the same. Therefore, the combinations of the concentrator and turbine have to be considered in the performance analysis of the system. Figure 1,2.

In this study, the airfoil type concentrator with flap is chosen. In the performance analysis the combination of the wind turbine and concentrator is considered. The airfoil type concentrator-wind turbine performance depends on the the dimensions of the geometry, airfoil shape and the position of the flap with respect to main part of concentrator. Works in the literature showed that the effects of the design parameters on the flow through the concentrator are investigated separately. As the interactions between the design parameters are very important, the interactions between parameters have to be considered in the performance analysis of the concentrator-wind turbine combination. In the optimization analysis the Response Surface Method with 2 D CFD analysis is used. After the

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Figure 1: Flange Type Concentrator.

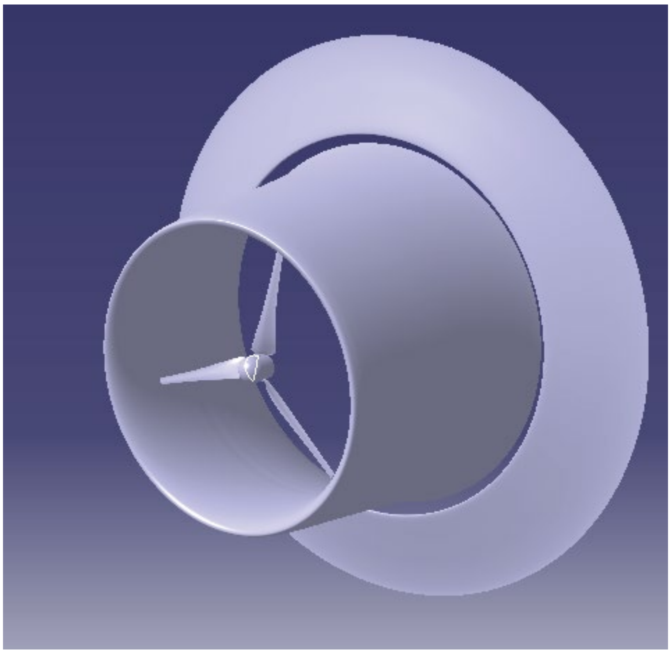

Figure 2: Airfoil Type Concentrator.

optimization analysis, the 3D CFD analysis is applied to the system to get performance of the system with and without concentrator.

Methodology

Geometry of Concentrator-Wind Turbine Combinations

The SG 6043 airfoil which has a high lift coefficient is chosen for both the main concentrator and flap [14]. The concentrator geometry with flap is given in Figure 3. The geometric parameters considered in the optimization analysis are; x/c1, y/c1, c1/D, c2/c1, α, and δ. D is the rotor diameter of the wind turbine and x, y and δ define the position of the flap with respect to the main airfoil. All optimum geometric parameters are obtained as a function of the rotor diameter of the turbine, D.

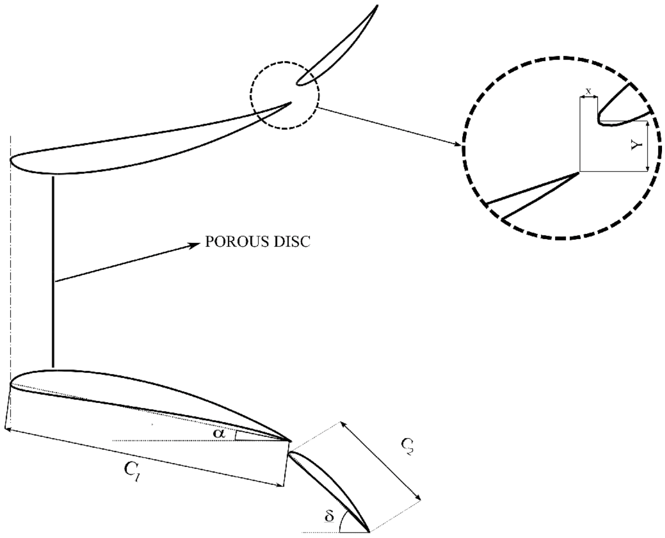

Figure 3: Geometry and parameters of the concentrator with flap.

In the verification analysis, the experimental work by Karlsen [15] is used. In this work the NREL S826 blade profile was applied. Also this profile has been chosen in some numerical and experimental studies in the literature [16-18]. Therefore, the NREL blade profile for the wind turbine is chosen in the verification analysis. The rotor diameter is chosen to be about 0.9 m.

The porous disc represented turbine is located at the narrowest cross-section of the concentrator with flap. The optimum values of the geometric parameters are obtained after the optimization studies with 2D CFD analyses and Response Surface Method. More details on optimization procedure are given by Koc and Yavuz [19].

CFD Analysis

A commercial CFD solver ANSYS-FLUENT is used to solve RANS equations for a steady flow. The k-ω turbulence model is chosen as its ability to model boundary layer separation in adverse pressure gradients. Green-Gauss cell-based discretization method is chosen as a solver in the CFD analyses. Also, the second-order scheme is used for the discretization.

The verification study is carried out with a turbine without concentrator by referring experimental work [15]. The computational domain used for the computations is shown in Figure 4. The computational domain has dimensions of 3D in radial direction and 5D in axial direction. Flow field around the turbine is assumed to be rotationally periodic. This reduces the number of cells one-third. A cylindrical domain is placed around the rotor and Moving Reference Frame model is used to give rotor rotation.

In the mathematical modeling of the wind turbine-concentrator combination a large computational domain (5D in radial and 5D in axial directions) is chosen to avoid wall effect, as shown in Figure 5. Boundary conditions are; velocity inlet (10 m/s), pressure outlet, periodic boundaries and wall. Inflation layer is used in boundary layer region for capturing velocity gradient. The first layer distance from blade surface is set to be 0.005 mm to keep the value of the y+ ( ) below 5.

The power coefficient is defined as

$$C_p = \frac{Tx\omega}{\frac{1}{2}\rho U\infty^3 A}$$

where T is the torque, ω is the angular velocity, U_∞ is the free wind speed and A is the rotor area. The tip speed ratio is defined as

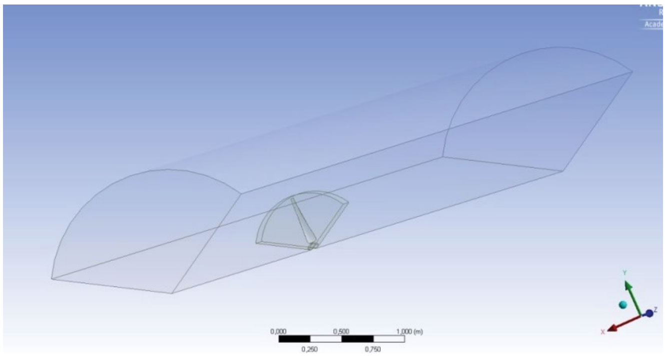

Figure 4: CFD domain of the bare turbine.

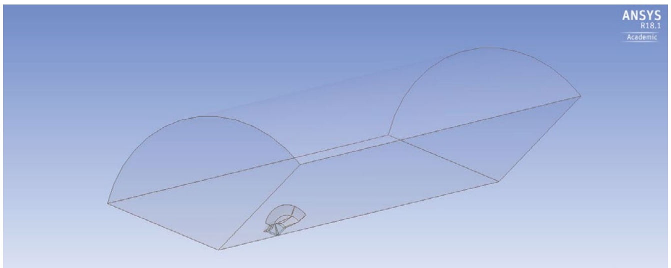

Figure 5: CFD domain of the wind turbine-concentrator combination.

$$\lambda = \frac{\omega R}{U\infty}$$

where R is the rotor radius. In the analysis the tip speed ratio is taken to be an independent variable.

Results and Discussions

The results of the verification analysis of the wind turbine without concentrator are given in Figure 6. The results show that CFD results are lower than experimental data [15]. As shown that depending on the tip speed ratio the difference between the CFD and experimental data is about six percent. This indicates that the CFD methodology is correctly constructed. The difference can be due to the error on the velocity measurements and taken the average value of the experimental data.

The optimum parameters leading maximum flow speed increase at the turbine zone in the concentrator are obtained to be as 5% (x/c_1), 2% (y/c_1), 10.2° (α), 0.4 (c_2/c_1) and 75° (δ). At these optimum geometric parameters, the wind speed increase at the wind turbine zone in the concentrator is about 1.25 times higher. The analysis show that the wind speed increases linearly with the length of the concentrator as reported in the literature [3,20]. Therefore, the ratio of the c_1/D is taken to be 1 in the performance analysis (C_1=D=0.9m). Consequently, knowing the rotor diameter of the wind turbine gives all optimum geometric parameters of concentrator leading maximum

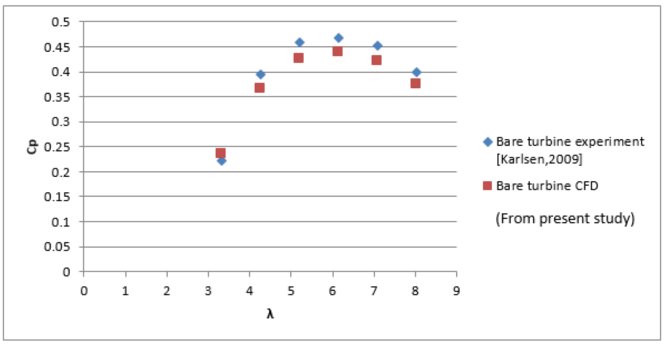

Figure 6: Results of the Verification analysis.

free wind speed increase.

Using the optimum geometric parameters of the wind turbine – concentrator combinations, the performance analysis of the system are determined by the 3D CFD analysis. Figure 7 shows the concentrator effects on the power coefficient or efficiency of the system. The value of the C_p is obtained as 0.44 for bare turbine and 1.11 for wind turbine –concentrator combination at the tip speed ratio of approximately λ ≈ 6. Bear in mind that, in the definition of the power coefficient, the free wind speed, 10 m/s, is taken into account. The power coefficient increases by 2.5 times compared to bare turbine. The power coefficient is higher for all other tip speed ratios for the wind turbine with concentrator.

The pressure distributions on the surface of the wind turbine blade without and with concentrator obtained at the speed ratio λ =6 are shown in Figure 8 and 9 respectively. Comparing pressure levels in suction and pressure sides of the blade, suction side pressure is lower and pressure side is higher for the case of the wind turbine with concentrator. This situation leads to acquire more torque from turbine with concentrator.

Also, local pressure distributions around the turbine for both cases are given in Figure 10 and 11. As it is seen, the local pressure difference is higher for concentrator case between front and behind the turbine blade. For bare turbine blade the pressure reaches to 168.2 Pa and -1713 Pa in front and behind the blade, while it reaches to the values of 290 Pa and -2366 Pa for the wind turbine with concentrator.

Conclusion

The optimization analysis of the combinations of the wind turbine and concentrator leading to maximum wind speed increase at the

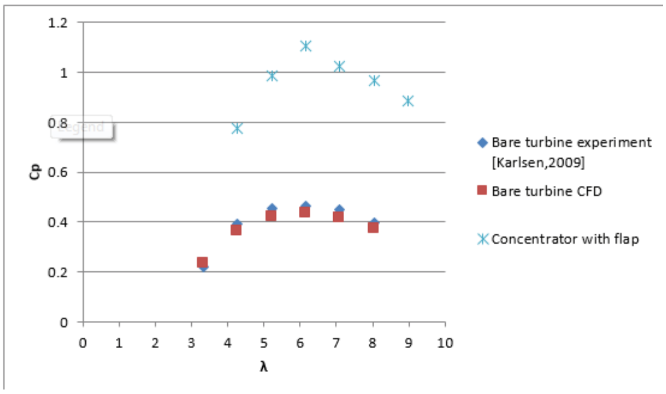

Figure 7: Variation of the power coefficient with tip speed ratio for wind turbine with and without concentrator.

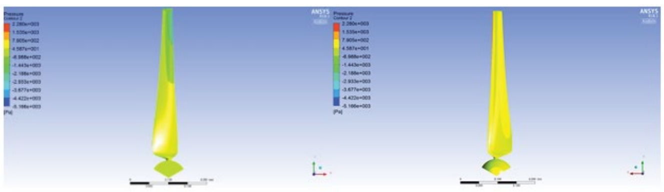

Figure 8: Pressure distribution of the bare turbine (suction and pressure sides), λ = 6.

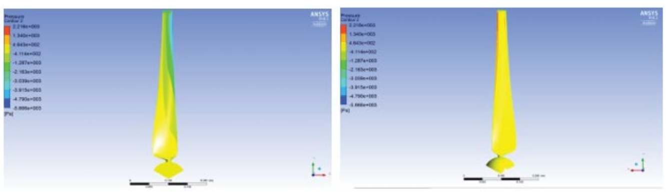

Figure 9: Pressure distribution of the turbine with concentrator (suction and pressure sides), λ = 6.

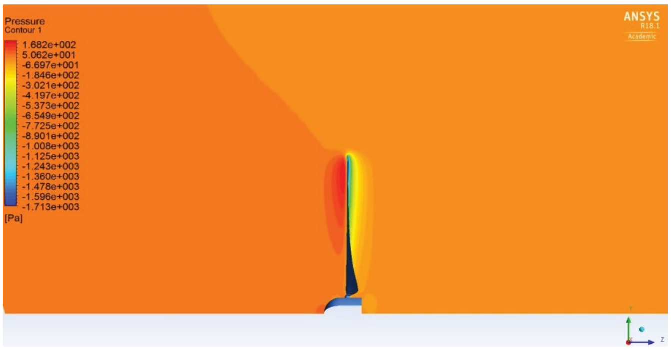

Figure 10: Local pressure distribution around bare turbine, λ = 6.

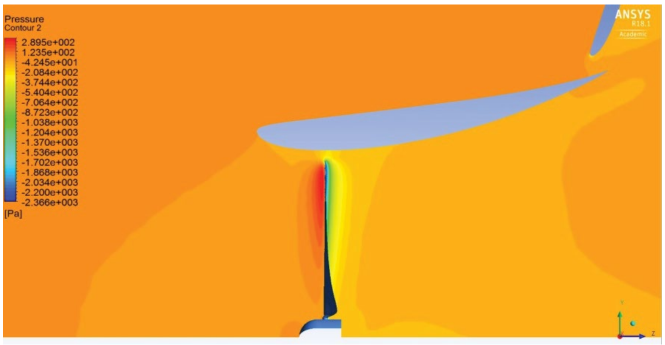

Figure 11: Local pressure distribution in the flow field of the turbine with concnetrator, λ = 6.

zone of the wind turbine in the concentrator is considered. Airfoil type concentrator with flap is chosen. The porous disc model is used to represent the wind turbine in the concentrator. The Response Surface Method with the 2D CFD analysis is applied in the optimization analysis.

Conclusions drawn from the study are;

•The location of the flap with respect to the main concentrator plays important role on free wind speed increase.

•The optimum geometric parameters leading to the maximum wind speed increase in the concentrator are as 5% (x/c1), 2% (y/c1), 10.2° (α), 0.4 (c2/c1) and 75° (δ).

•Knowing the diameter of the wind turbine rotor gives all optimum geometric parameters of the concentrator leading the maximum free wind speed increase in the concentrator.

•Concentrator increases the free wind speed and power output by the factors of about 1.3 and 2.5 respectively.

•Due to the increasing free wind speed at the zone of the wind turbine in the concentrator, the wind turbine with concentrator can be used to produce more energy from the wind and also it can be used to produce the energy in the area with poor wind statistics.

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