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Numerical Study on the Influence of Torque Performance Caused by Deflectors on Darrieus Wind Turbines

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ABSTRACT

This paper investigates the effects on the torque performance caused by deflectors of the Darrieus turbine. Various deflectors were placed in front of the turbine and disrupted the wind flow before it came into contact with the turbine blades. Using numerical method, this study aims to find the deflector's optimum geometric shape, offset distance, and dimension required for the turbine to produce the highest torque. This study utilizes flow simulation analysis to simulate the deflector effect on Darrieus turbine. The result of this study is the optimum deflector geometry and offset distance for producing highest turbine torque output. From the data gathered it is shown that a deflector with triangular cross-section with the size of turbine diameter placed 400 mm offset to the right of the turbine produces the best result. Turbine with this deflector configuration produces 1.24 Nm of torque, eight times higher than its non-deflector counterpart yields 0.14 Nm.

1. Introduction

In pursuing the growing demand for clean and sustainable energy sources, wind stands out as a prominent and rapidly expanding sector. Wind as an energy source has had its origin way back in the ancient times, with the vertical axis windmills found at the Persian-Afghan borders around 200 BC and the horizontal-axis windmills of the Netherlands and the Mediterranean following much later (1300-1875 AD) [1]. Wind power has emerged as a highly prevalent and extensively utilized form of renewable energy, with mechanical equipment being employed to convert it into electrical energy [2]. Utilizing wind energy for electricity generation, instead of fossil fuels, has the dual benefit of conserving conventional energy resources and safeguarding the environment [3]. In the last decade, the global wind energy capacity has increased 2012 to 2021 [4]. The rate of development and deployment accelerated rapidly in recent years due to its several advantages, including being cost-effective, reliable, and environmentally friendly [5].

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In the present day, numerous countries are allocating a growing amount of funds towards the establishment of wind turbines [6]. Indonesia is one of the leading countries in wind power development in Southeast Asia, with a capacity of 9,861 MW. However, the development of wind power in Indonesia poses some challenges. According to the Indonesian Ministry of Energy and Mineral Resources 2020-2024, the wind mean annual speed in Indonesia is only between 3 m/s – 6 m/s, only half to that of the countries in the northern and southern hemispheres that have wind speed higher than 8 m/s. This lower speed happens due to Indonesia's location, which is located on the equator with warm air and low pressure [7].

The two most common wind turbine configuration is Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). Horizontal axis wind turbines (HAWT) are the most common type of wind turbine design due to their superior power performance compared to the others [8]. However, Horizontal axis wind turbines require substantial installation space, and the chosen location must have abundant wind energy resources to accommodate their considerable dimensions and address the noise issue at the same time [9]. The VAWT configuration required minimum wind speed of only 2 m/s, which is more suitable to be implemented in Indonesia [7]. Besides that, VAWT exhibits substantial potential in urban settings as they uphold a notable power coefficient [10]. The unique attributes of vertical-axis wind turbines render them appropriate for urban settings [11]. In the past few years, there has been rapid development in kilowatt-level vertical axis wind turbines (VAWTs) within urban areas [12]. However, the location of urban installations which have different geometric conditions affects turbine production [13]. The constrained power coefficient poses a limitation on the extensive utilization of vertical axis wind turbines (VAWTs) [14]. Basic types of vertical axis wind turbines (VAWTs) commonly include the H-Rotor type, Darrieus type, and Savonius type [15]. The Darrieus turbine, classified as a lift-type vertical axis wind turbine (VAWT), possesses the advantage of functioning effectively at low wind speeds [16]. However, it exhibits a drawback in terms of aerodynamic performance when compared to horizontal-axis turbines [17]. Therefore, improvements are needed to increase VAWT efficiency.

Numerous attempts have been undertaken to enhance the power efficiency of vertical axis wind turbines (VAWTs), such as refining airfoil selection and optimization [18]. Chen *et al.,* [19] found that the thickness-chord ratio has a significant influence on the power coefficient. De Tavernier *et al.,* [20] compared optimized airfoils of VAWT with reference airfoils from the first generation. The optimized airfoils demonstrate superior performance in power coefficient compared to the reference airfoils [20]. Moreover, the utilization of variable-pitch methods has also been implemented to discover the optimal outcome in power production [21]. The adjustment of the pitch angle represents a prospective factor for improving the performance of VAWT turbines [22]. A vertical-axis wind turbine with fixed-pitch straight blades undergoes consistent changes in the wind attack angle as a result of its rotation pattern, resulting in poor power generation. To address the problem, some studies investigated blade pitch control technology, which involves adjusting the pitch angle of a blade to modify the wind attack angle, thereby altering the aerodynamic forces acting on the blade [23].

Some studies focus on minimizing aerodynamic losses [24]. With the advantages of low cost and impressive visualization capabilities, Computational Fluid Dynamics (CFD) technology has prompted a growing number of scholars to explore the aerodynamic traits of wind turbines using this technology [25]. Villeneuve *et al.,* [26] investigate the impact of the blade support structures on the performance of a single-blade vertical-axis wind turbine through three-dimensional URANS simulations. The findings indicate that the efficiency of the turbine is greatly influenced by the placement of the struts. Ashwindran *et al.,* [27] conducted research examining how blade geometry influences the airflow interaction with the wind. They effectively formulated mathematical methods for shaping blade morphology to impact the drag generated by the turbine. Some modifications are applied to improve VAWT performance, including the design of the turbine itself, such as airfoil shape and size, tilt angle, and pitch angle.

On the other hand, some researchers preferred to rely on augmentation devices such as diffuser, guide vanes, stator, shroud, plate, deflector, or duct to enhance the wind turbine efficiency [28]. Adding a deflector to the conventional wind turbine system was discovered to be a simple way to enhance the coefficient of performance and reduce the negative torque induced from the returning blades [28]. Wong *et al.,* [29] demonstrated that the deflector functioned as a power-enhancing mechanism, leading to an improved efficiency of the vertical axis wind turbine. In essence, the deflector helps minimize the detrimental effects that can affect the overall efficiency of the wind turbine [30]. This function is important because negative torque can reduce the efficiency of a wind turbine. The deflector serves to direct and concentrate the airflow, aiming to enhance positive torque and diminish negative torque in wind turbines. By employing the deflector, the airflow can be efficiently directed to optimize energy production, amplifying the generated torque while mitigating the negative forces that influence the overall performance of the wind turbine [31]. According to the numerical simulation, De Tavernier *et al.,* [32] found that the deflected mass flow contributes to the power enhancement of the double-rotor layout.

The study about deflector that has been conducted in the past only considers the offset distance of the deflector to the turbine. This study proposes an investigation of the changes in the geometric shape and size of the deflector. This study utilizes a transient 3D model to compare and optimize the performance of the Darrieus wind rotor by varying the deflector geometry. The primary objective of this research is to determine the optimal shape, size, and offset distance for the deflector, to maximize the torque generated from wind energy. The overarching goal is to uncover a novel approach that can effectively improve the efficiency of Darrieus turbines in the foreseeable future. The results of this research will yield an accurate geometric model that can be implemented in front of Darrieus wind turbines.

2. Methodology
2.1 Numerical Equations

In the fast-growing application of computational fluid dynamics (CFD) within decades the significance of numerical flow simulations in the design of hydraulic machinery has grown to a considerable extent. At present, CFD simulations can often replace laboratory experiments due to the fact that even complex geometries and entire machines can be modeled. Many types of research were conducted to demonstrate the influence of a modified Darrieus turbine on its aerodynamic performance. However, the influence of deflector variables and their interactions on the aerodynamic performance was not examined in detail in these works.

The aerodynamic efficiency of the Darrieus wind turbine relies on the flow properties surrounding its blades [33]. From this point of view, the present study is focused on suggesting deflectors' geometrical impact using the numerical optimization method on the torque yields. In this paper, the CFD software used to do numerical analysis is SolidWorks flow simulation. The Flow algorithm used Navier-Stokes Equation to solve the flow problem which is an equation of mass, momentum, and energy conservation laws [34,35].

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) + \frac{\partial P}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\tau_{ij} + {\tau_{ij}}^R\right) + S_i \tag{2}$$

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_j}\left(u_j\left(\tau_{ij} + {\tau_{ij}}^R\right) + q_i\right) + \frac{\partial p}{\partial t} - {\tau_{ij}}^R \frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H \tag{3}$$

$$H = h + \frac{u^2}{2} \tag{4}$$

Here, the term $-\rho uj\ '\ ui\ '$ is the Reynolds stress model, *ui* is the velocity component, *P* is fluid pressure, ρ is fluid density, τ is deviatoric stress tensor, ε is the dissipation of turbulent kinetic energy, k is turbulent kinetic energy, h is enthalpy, μ is dynamic viscosity of fluid, μ_t is eddy viscosity, Q_H is the amount of heat, and S is entropy, i and j is the direction of vector. While where Cμ =0.09, Cε1 = 1.44, Cε2 =1.92, σk=1, σε=1.3, σB =0.9, CB =1 if P_B >0, CB =0 if P_B <0.

The flow simulation modeled turbulence using the modified *k-ε* model, this model makes the equations easier to solve, this model proposed by Lam and Bremhorst (1981) describes laminar, turbulent, and transitional flows of homogeneous fluids consisting of the following turbulence conservation laws

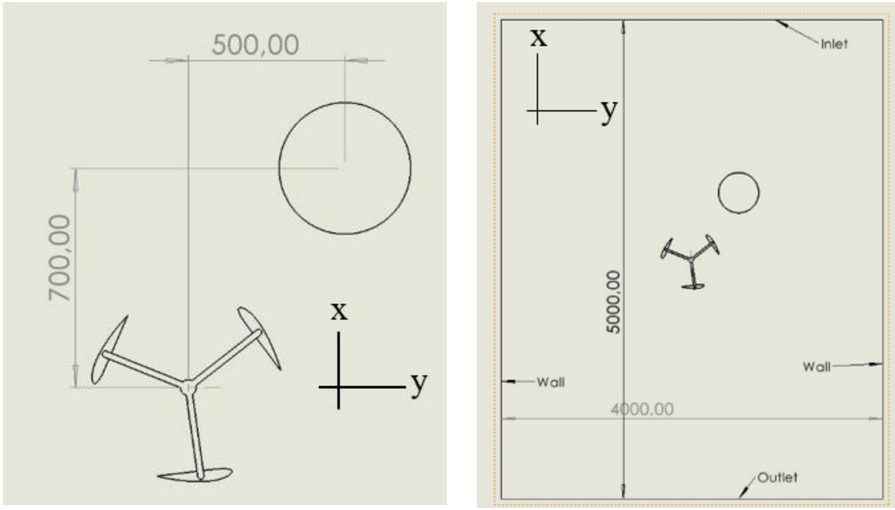
$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho k u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right) + {\tau_{ij}}^R \frac{\partial u_i}{\partial x_j} - \rho\varepsilon + \mu_i P_B \frac{\partial \rho\varepsilon}{\partial t} + \frac{\partial \rho\varepsilon u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_i}{\sigma_i}\right)\frac{\partial k}{\partial x_i}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1 {\tau_{ij}}^R \frac{\partial u_i}{\partial x_j} + C_B \mu_t P_B\right) - f_2 C_{\varepsilon 2}\frac{\rho\varepsilon^2}{k} \tag{5}$$

$$\tau_{ij} = \mu S_{ij}, {\tau_{ij}}^R = \mu_i S_{ij} - \frac{2}{3}\rho k \delta_{ij}, S_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}, \tag{6}$$

$$P_B = -\frac{g_i}{\sigma_B}\frac{1}{\rho}\frac{\partial \rho}{\partial x_i} \tag{7}$$

2.2 Boundary Condition

The turbine design used in this study is NACA 4415 airfoil. Four different shapes of deflector cross sections are tested in this simulation, which are circle, rectangle, triangle, and diamond. The deflector is installed at the front of the turbine and placed offset to the right. This configuration aims to increase the torque produced by the turbine and this study's goal is to find the optimum deflector cross-section shape and distance from the turbine. The inlet works as a velocity inlet with a velocity of around 4.5 m/s. This velocity is chosen as the middle ground from Indonesia's average wind speed of 3-6 m/s taken from the data of the Ministry of ESDM. The wall works as a smooth wall so that the wake induced by the wall can be neglected, and the outlet works as a wind outlet that has a pressure of 101325 Pa. The turbulence model in this study is modeled using the modified *k-ε* model. The schematic of this setup can be seen in Figure 1.

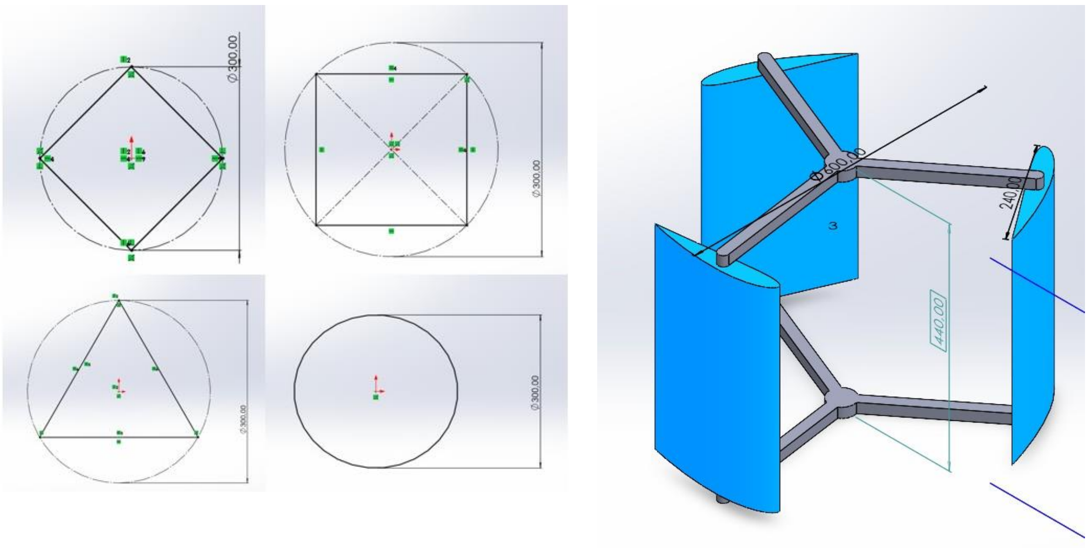


(a) (b)

Fig. 1. The schematic setup for (a) Simulation setup with circle deflector, and (b) Boundary condition setup

2.3 Model of the Turbine

This study runs multiple simulations on every case. The data is collected from each shape of the deflector, each size of the deflector, and offset distance variation. The x-distance of 700 mm was chosen as the independent variable. In this study, the torque produced by the turbine with each of the four shapes of deflector are compared. For each shape, the simulation runs between the offset distance y of 0 to 500 mm with 100 mm increments, and for every 100 mm the diameter of the deflector was varied from 0,1 to 1 times of the turbine diameter DT. The shape and geometry of deflectors and the 3D model of the turbine are shown in Figure 2.



(a) (b)

Fig. 2. (a) Deflectors shape and geometry, and (b) 3D model of the turbine

2.4 Meshing Approach

SolidWorks Flow Simulation is based on an immersed body mesh approach. This mesh can be defined as a set of rectangular cells, which are adjacent to each other and the external boundary of the computational domain. In this approach the creation of the mesh starts independently from geometry itself and the cells can arbitrarily intersect the boundary between solid and fluid. The advantages of these Cartesian-based meshes include simplicity, speed, and robustness of the mesh generation algorithm; minimal local truncation errors; and robustness of the differential schemes [31]. The mesh domain of the simulation can be seen in Figure 3.

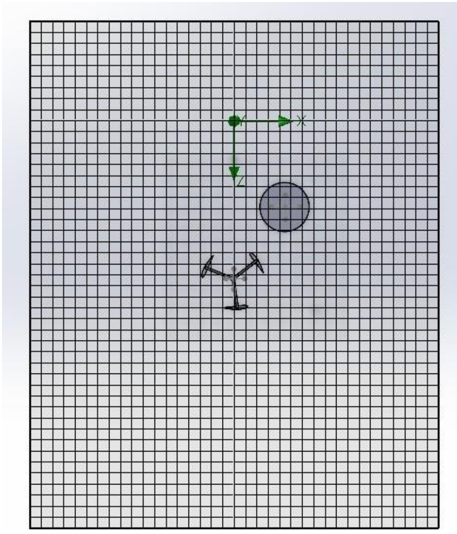


Fig. 3. Mesh domain for the simulation

To ensure the highest possible level of precision while taking into account limited computational resources, the author of this experiment selected a particular type of mesh. Given the need to conduct multiple simulations, an automatic global meshing method was employed, utilizing a level 6 mesh. This approach enabled the collection of data that was both highly accurate and efficient, thereby maximizing the potential of the available resources.

3. Results

3.1 The Torque Performances

The simulations were performed for all types of cross-sectional shapes of the deflector. For each cross-sectional shape, the offset distance of the deflector was varied, and for every distance the diameter of the deflector was varied. The offset distance ranged from 0-500 mm in 100 mm increments, while the diameter ranged from 0.1 to 1 times the turbine diameter. The author chooses the offset distance range for a specific reason. The deflector's effect decreases after 300mm, so continuing the simulation with a further distance can result in the turbine generating the same amount of torque as a non-deflector turbine. Based on previous simulations conducted by the authors, a 700mm x-axis offset has been chosen. The simulations indicated that increasing the x-axis offset number results in decreased torque production by the turbine, and negative torque may even occur at certain points. On the other hand, if the offset is less than 700mm, the blade could potentially collide with the deflector during rotation. The torque performance curves as the function of each shape of the deflector are shown in Figure 4. It is observed from the graph that the increase in the diameter of the deflector results in an increase in the dynamic torque. However, we observe that using the deflector, the turbine certainly has higher torque compared to turbines without a deflector. At peak conditions, the increase is considerably significant and it is about 50%. It is evident that with the increasing diameter of the deflectors, the region behind the deflector and the wake of the turbine becomes less turbulent.

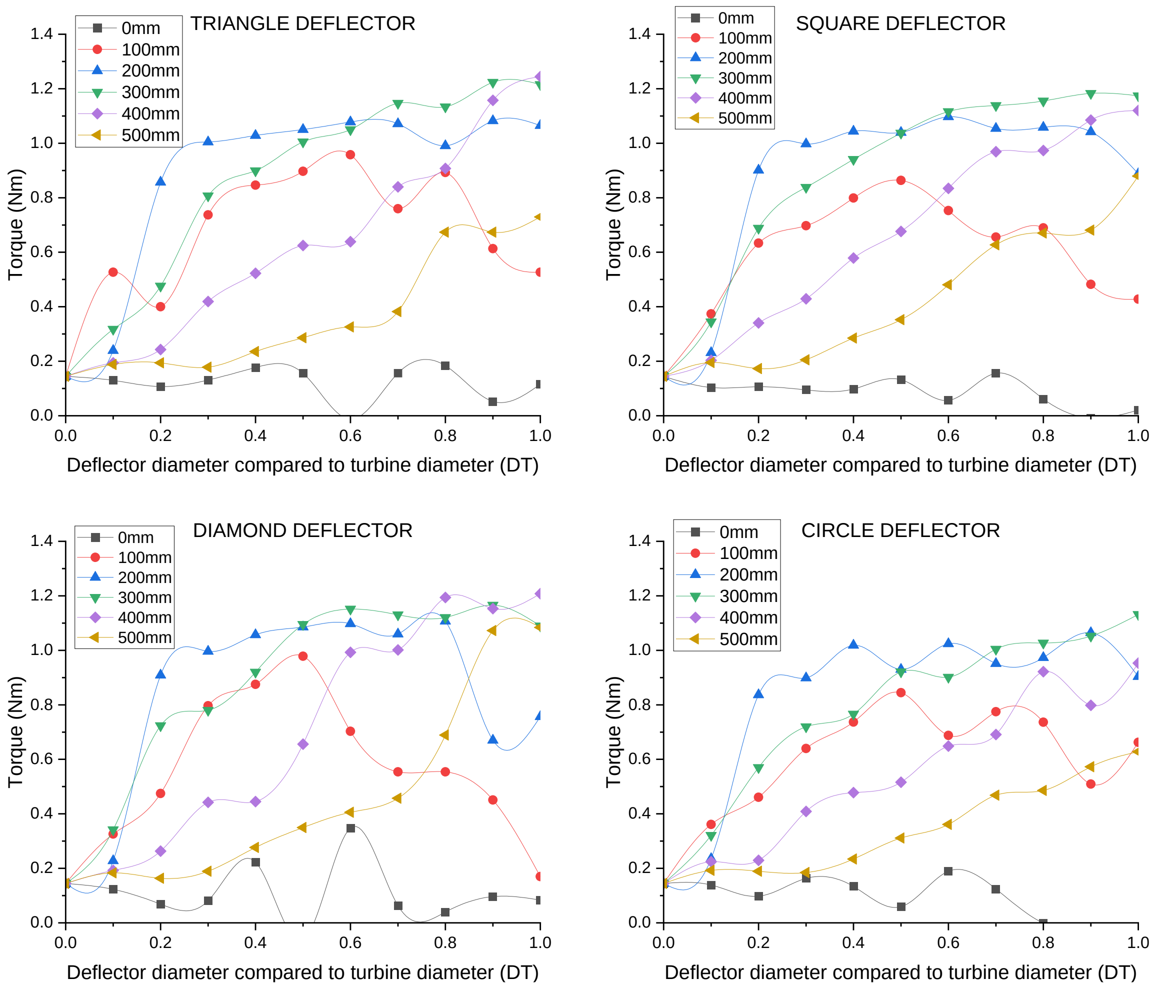
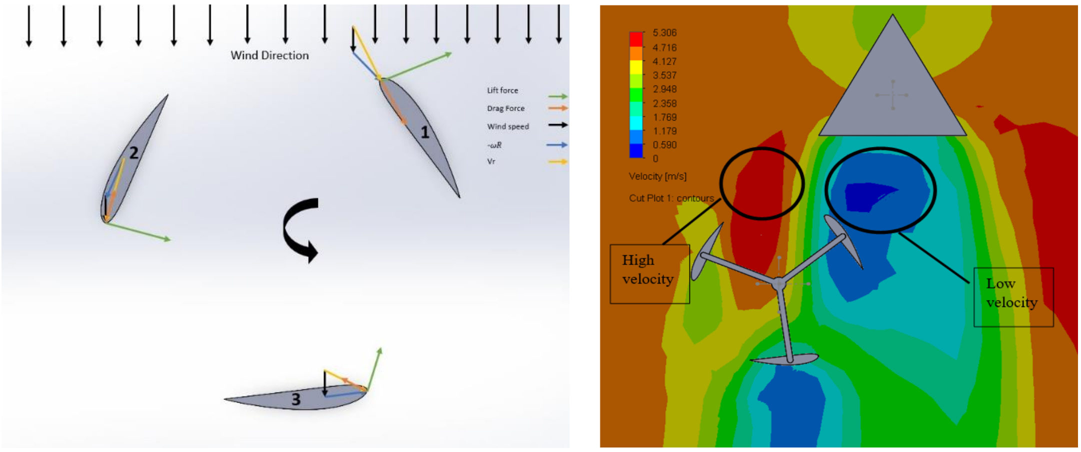


Fig. 4. The torque performance curves as the function of each shape of the deflector

3.2 Performance Comparisons between Deflector Shapes

It can be seen from the results that some distances can lead to a decrease in torque at a certain diameter. The Daeriuss turbine rotates with the help of lift force. Besides the lift force, the airfoil on each blade produces drag force. The diagram of the force acting on the turbine is shown in Figure 5(a). Figure 5(b) shows a wind flow illustration with a triangle deflector. From the figure, blade number 1 generates negative torque. To overcome this condition, the deflector is added to decrease wind velocity around blade number 1 and increase the velocity around other blades, and at the same time decrease the amount of negative torque and increase the positive torque generated by the turbine. Therefore, the net torque of the turbine increases. In the case of negative net torque, the disruption of the wind flow caused by the deflector also decreases the wind velocity on blade number 2. This is why negative net torque usually happens at 0 mm offset distance y where the wind velocity on both blade number 1 and blade number 2 are low.



(a) (b)

Fig. 5. (a) Force diagram acting on the turbine, (b) Wind flow around the turbine with triangle deflector

The highest torque produced by the turbine for each deflector shape are as follows: 1.13 Nm for the cylinder at 300 mm distance with the size of turbine diameter, 1.20 Nm for the diamond at 400 mm distance and with the size of turbine diameter, 1.17 Nm for square at 300 mm distance with the size of turbine diameter, and 1.24 Nm for the triangle at 400 mm distance with the size of turbine diameter. Performance comparisons between deflector shapes are shown in the Figure 6.

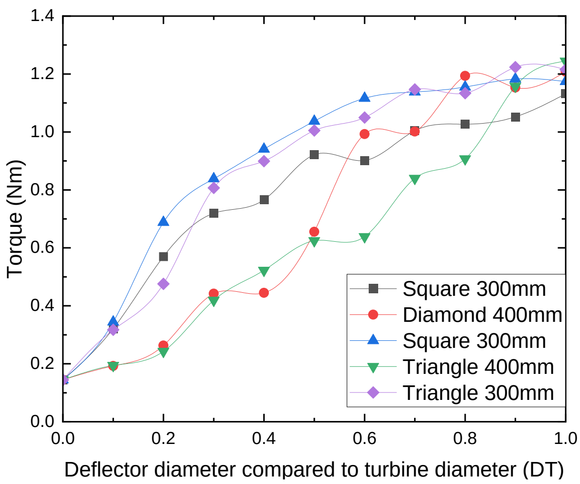


Fig. 6. Maximum torque produced by each deflector with optimum distance

From Figure 6, it can be seen that when the diameter of the deflector is between 0.1 and 0.6 DT, the highest torque was produced by the square deflector, whereas between 0.7 and 1 DT, the highest torque produced varies between triangle and diamond. What we need to notice is that each shape gives a positive increase in torque produced by the turbine. Based on the maximum torque values, the triangular deflector demonstrates the highest torque at 1.24 Nm, followed by the diamond deflector with a value of 1.20 Nm. Conversely, the circular and square deflectors exhibit lower maximum torque values. Based on these considerations, the triangular deflector achieves a combination of high maximum torque and relatively low minimum torque. Consequently, among the four provided deflector types, the triangular deflector is deemed the most optimal in torque generation based on the available data. With a triangular deflector, the turbine produces torque eight times higher than its non-deflector counterpart.

The triangular deflector utilizes a uniform distribution of air pressure across its surface. Pressure can vary on a triangular shape depending on the angle and geometry of the triangle. Generally, the pressure is higher on the steeper or sharper sides of the triangle and lower on the more gentle or curved sides. By capitalizing on this principle, the triangular deflector maintains airflow stability around it, avoiding turbulence that can decrease torque efficiency. With its evenly distributed pressure, the triangular deflector generates consistent and strong torque, positively impacting the overall performance of the turbine [36]. The idea of this deflector design on the Darrieus turbine is advantageous technically for optimizing the torque yields in the power generation fields.

4. Conclusions

Adding a deflector in front of a Darrieus VAWT (Vertical Axis Wind Turbine) can significantly enhance the turbine's torque output. The deflector redirects the airflow towards the turbine blades, leading to an amplified lift force and thereby increasing the torque output. The effectiveness of the deflector depends on its shape, with a triangular deflector proving to be the most efficient. It concentrates the airflow towards the turbine blades, optimizing their performance. The recommended configuration involves positioning the deflector at an offset distance y of 400 mm, with a diameter matching that of the turbine. In this study, the highest torque output was achieved with a triangular deflector positioned offset 400 mm to the right of the turbine and having the same diameter as the turbine. The resulting torque output of 1.24 Nm was eight times greater than that of a turbine without a deflector which produced a torque of 0.14 Nm. The study utilized a computational fluid dynamics (CFD) model to simulate the Darrieus VAWT. Wind speed was set at 4.5 m/s, and the wind direction corresponded to the negative x-direction. The findings indicate that incorporating a deflector into a Darrieus VAWT constitutes a highly effective approach for maximizing torque yields. This advancement holds great promise for turbines employed in electricity generation or powering other machinery.

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