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Wind flow characteristics through shrouded wind turbine using ANSYS

Mais Alzgool[1*], Obada Alrefai[2], Ahmad Alamleh[3], Mohammad Alyaqoub[4]
[1,2,3,4]Energy Engineering Dep. Zarqa University Zarqaa, Jordan; malzgool@zu.edu.jo (M.A.) obada123alrefai@gmail.com (O.A.) ahmadnumandx@gmail.com (A.A.) Mohmmadalyaqoub@gmail.com (M.A.).

Abstract: Wind energy is a mature and quick-growing source of energy in many nations. New wind energy technologies must be introduced to increase effectiveness and reduce the cost of wind turbine installation. Wind energy conversion experts believe that shrouded wind turbines are a promising technology that could raise output and efficiency levels. A low-pressure zone is created behind the turbine because of the shroud's unique structure. As a result, the turbine draws in greater mass flow to produce more power. With the aid of this innovative technology, wind turbines could be used in populated areas where lower wind speeds could be captured. In this study, a comparative analysis has been applied to different designs of shrouded wind turbines to analyze the wind speed, pressure, output power and power coefficient. ANSYS software has been conducted in this paper where the results obtained that the output power could be increased up to 3-4 times compared to the bare wind turbine, also a high-power coefficient could be reached up to 83.1%.
Keywords: *ANSYS, Diffuser, Shrouded wind turbine (SWT), Wind energy, Wind flow.*

1. Introduction

The continuous use of traditional energy sources (non- renewable) increases environmental problems such as global warming, and climate change, and then increases the earth's temperature [13, 14]. Wind energy is the energy obtained from the wind and it is one of the oldest energy sources exploited by humans [1, 15]. Today wind energy is the most established renewable energy source [16-18].

Jordan is considered as one of the first countries that exploited renewable energies in general, wind energy was very popular due to Jordan's strategic location. Where wind speeds in Jor- dan are considered suitable for wind power projects [19-22]. Therefore, wind turbine innovation is especially important in optimizing the utilization of wind energy, especially in areas with low wind speed characteristics. One of the main problems of wind energy is the efficiency of the rotor which is represented by the Coefficient of Performance (Cp) or the Betz limit [23-25]. The wind turbine's overall efficiency is affected by rotor, mechanical, and electrical efficiency. Furthermore, the change in the rotor's efficiency will significantly change the overall efficiency of the Wind turbine [2]. To exploit the relatively low wind speeds, a modern, advanced technology had to be found to exploit these speeds so, a Shrouded Wind Turbine (SWT) could be used. SWT is one of the developments in the wind turbine innovation concept which is equipped with a diffuser sheath on the rotor [2], [26-28]. SWT is an effective technology for improving the Betz limit which was created by Gilbert et al [3]. By recovering diffuser kinetic energy, the diffuser produces a greatly reduced pressure behind the turbine relative to that behind a conventional turbine (unshrouded). This causes more mass to flow through the shrouded wind turbine with at least as much pressure change as across the conventional turbine [4]. In other words, SWT is an optimized class of wind turbines that use a diffuser to accelerate and direct the airflow into the rotor to drive it for higher rotation speeds and then more power output [5]. Also, in general, SWT has more noise reduction, also could be installed in locations with low wind speeds.

However, shrouded wind turbines faces some challenges; although the power augmentation is considerable, the duct will increase the cost, with increasing the weight of the shrouded turbine, and this

* Correspondence: malzgool@zu.edu.jo

will increase the complexity and cost of installing the turbine [9, 34].

The most important aspect affecting the performance and efficiency of the shrouded turbine is the shape of the diffuser and the brim as shown in Figure 1 [35-40].

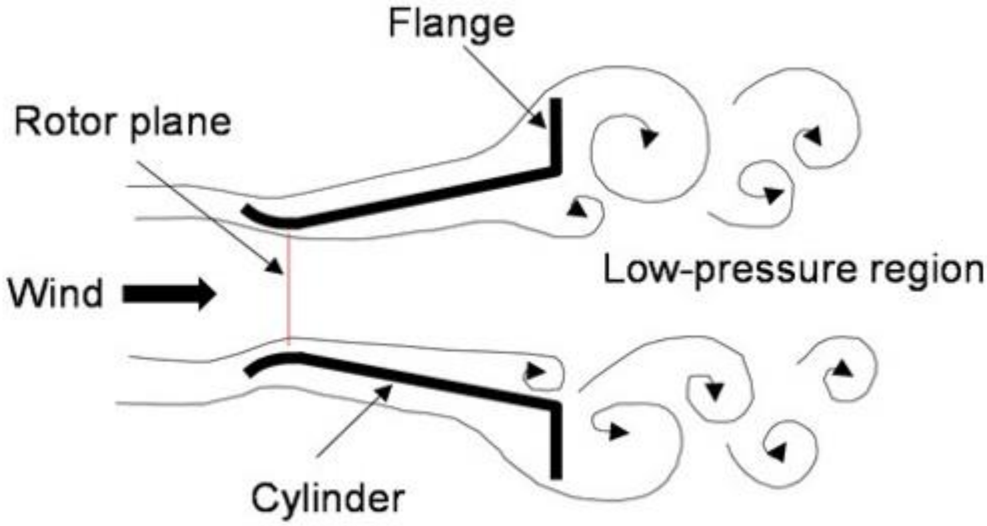

Figure 1.
Brimmed (Flanged) diffuser [6].

With diffuser shrouded turbine the mass flow rate of air through a turbine is increased by virtue of sub-atmospheric pressure at the diffuser exit plane [36, 37]. Thus, the output power could be exceeded above the Betz-limit with a ratio depending on the increment of the mass flow rate [7, 29].

In addition, the studies and results have proven that the angle of the brim could affect the performance of the turbine significantly [30-32]. It has been found that the optimal brim angle (θ) as shown in Figure 2 is $+10°$, in which this will increase the air speed and power by 4.83% and 15%, respectively. This increase is due to the variation in the magnitude of eddy generation behind the tip. This indicates that the nature of the flow separation points inside a shroud significantly affects the acceleration of airflow through the brimmed cover [8] [33-34].

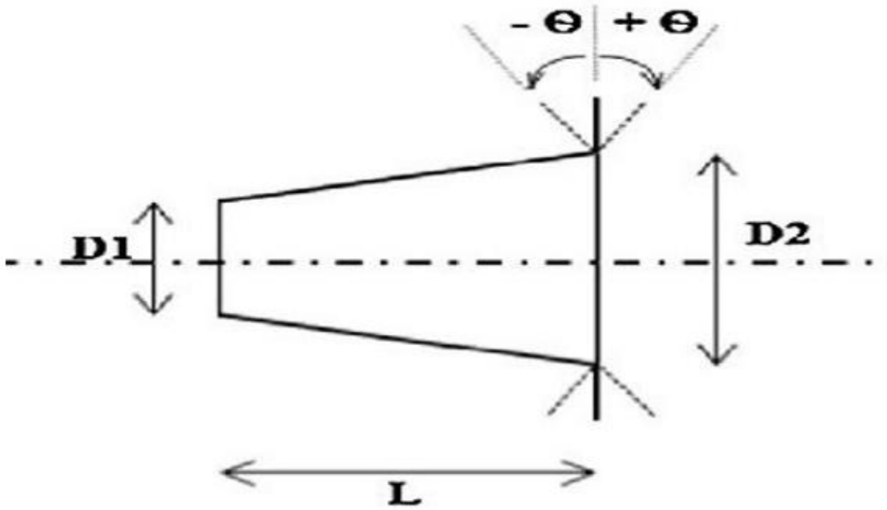

Figure 2.
Brimmed angle [8].

Thus, this study discussed the improvement of the rotor's efficiency using SWT. Also, a comparison between the shrouded wind turbine and the conventional wind turbine will be presented. Furthermore, a verification and validation of the four designs will be conducted via calculation and simulation using ANSYS software.

2. Methodology

2.1. Theoretical Analysis of Shrouded Wind Turbine

To analyse the SWT a control volume approach will be used [11]. The total pressure balance equation for the cylindrical control volume could be written as follows:

$$P_u + \frac{1}{2}\rho {V_u}^2 = {P_r}^+ + \frac{1}{2}\rho {V_r}^2 \tag{1}$$

$$P_r^- + \frac{1}{2}\rho {V_r}^2 = P_e + \frac{1}{2}\rho {V_e}^2 + \Delta P_d \tag{2}$$

$$P_e + \frac{1}{2}\rho {V_e}^2 = P_u + \frac{1}{2}\rho {V_w}^2 \tag{3}$$

Where:

${P_r}^+$ *and* ${P_r}^-$: The static pressure in front and behind the rotor plane respectively.

ΔP_d : The pressure drop by the diffuser.

V_u, V_r, V_e *and* V_w : The upstream, rotor plane, diffuser exit, and far-wake wind speeds respectively.

For the case of steady-state incompressible flow, the energy balance equation could be expressed and the extracted power will be [11, 12]:

$$P_{extraced\ by\ rotor} = Q\left[\frac{1}{2}\rho {V_u}^2 - \frac{1}{2}\rho {V_w}^2\right] - Q\Delta P_d \tag{4}$$

$$V_w = (1 - 2a)V_u \tag{5}$$

$$a = 1 - \frac{V_r}{V_u}$$

Where:

Q: The air flow rate.

ρ: The air density.

Assuming, the air is incompressible, and its density is frigid, the following constants could be found as follows:

$$\mu = \frac{V_w}{V_u} \quad (6)$$

$$\gamma = \frac{V_r}{V_u} \quad (7)$$

$$\beta = \frac{V_e}{V_r} \quad (8)$$

Where μ is the turbine speed reduction factor and γ is the speed up ratio while β is the diffuser inlet to outlet ratio. In order to predict the performance of a real diffuser, it is necessary to limit the range of variation of parameters for practical and mathematical reasons and for better design the variation ranges for β and ηd could be estimated as follows [11, 12]:

$$0.3 < \beta < 0.6$$

$$0.6 < \eta_d < 0.9$$

Then the power coefficient $\boldsymbol{C_P}$ will be:

$$C_P = \gamma[(1-\mu^2) - \gamma^2(1-\beta^2)(1-\eta_d)] \quad (9)$$

The physical estimation of total maximum power coefficient is:

$$C_P = \frac{16}{27}\gamma^2 \quad (10)$$

In this study, the wind speed Vu has been considered to be 4 m/s. And then the value of Cp of the four designs have been obtained based on equation 10 and assuming that the wind speed is $4\ m/s$ with 7 Tip Speed Ratio (TSR) as follows:

In the case of a straight diffuser without a brim where $Vr = 4.2\ m/s$, the speed-up ratio γ in this case will be:

$$\gamma = \frac{4.2}{4} = 1.05$$

$$C_P = \frac{16}{27}(1.05)^2 = 0.653$$

In the case of a straight diffuser with a brim where $Vr = 4.5\ m/s$, the speed up ratio γ and C_P will be:

$$\gamma = 1.125$$

$$C_P = 0.75$$

While in the case of a curved diffuser without a brim where $Vr = 4.1\ m/s$, the speed up ratio γ and C_P will be:

$$\gamma = 1.025$$

$$C_P = 0.623$$

And for the case of a curved diffuser with a brim where $Vr = 4.65\ m/s$ the speed up ratio γ and C_P will be:

$$\gamma = 1.1625$$

$$C_P = 0.801$$

It is clear from the results that the C_P value for the curved diffuser with brim has the highest amount among all the other studied cases with the highest speed-up ratio.

2.2. Designing of Shrouded Wind Turbine

The shrouded wind turbine is proposed as an innovative solution with the potential to increase both Cp and overall power generation. Figure 3 illustrates the design of the blade, the impact of the diffuser on one blade has been studied.

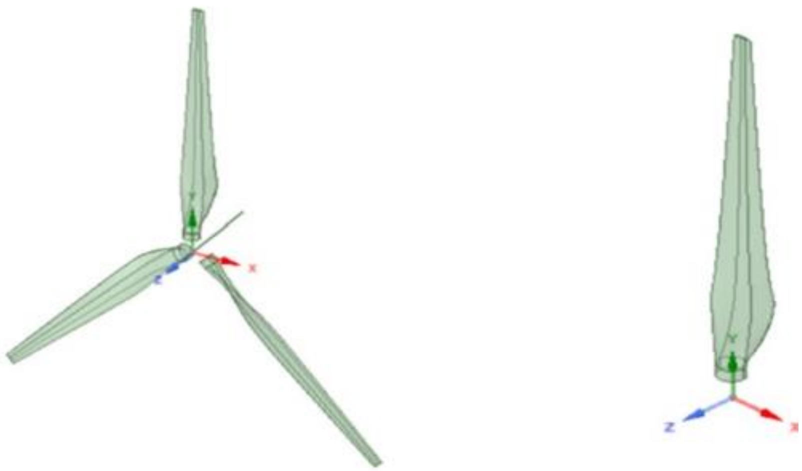

Figure 3.
Wind turbine blades' design using ANSYS [10].

This study has focused on developing four different designs of diffusers as shown in Figure 4. Each design was created with the aim of improving the performance of the shrouded wind turbine in terms of output power and rotor efficiency.

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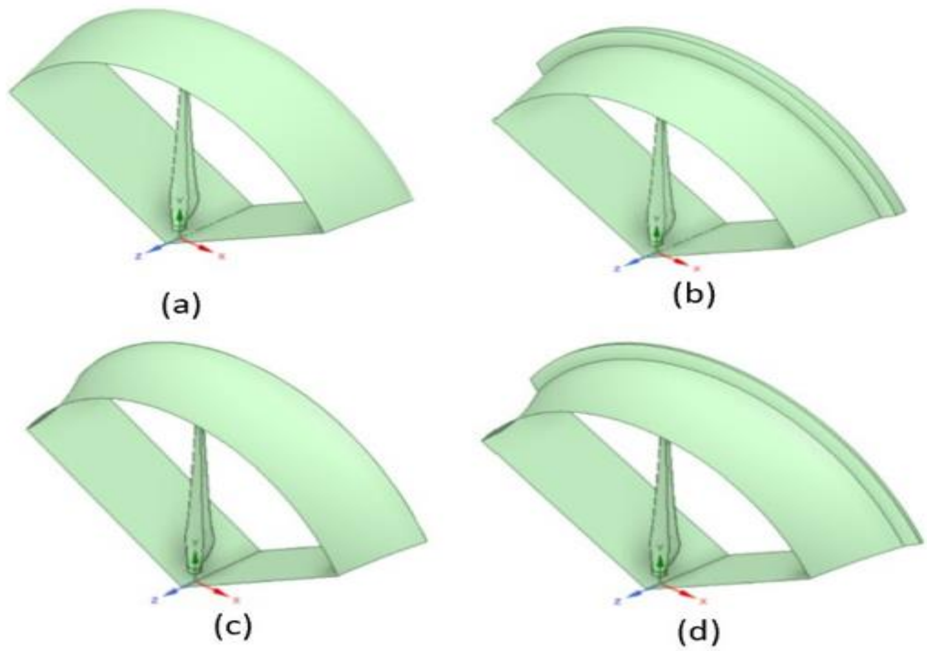

Figure 4.
Different designs of shrouded turbine.
Note: (a) Straight diffuser without brim.
(b) Straight diffuser with brim.
(c) Curved diffuser without brim.
(d) Curved diffuser with brim.

2.3. Numerical Flow Simulation

The general specifications of the diffuser design refer to the overall features and characteristics of the four designs studied in this study. These designs differ in terms of diffuser design; including whether they have a brim or not and whether they are straight or curved.

The simulations were performed under similar inlet and outlet conditions. Allowing for a direct comparison of the performance and characteristics of each design. Also, through the simulation the value of Vr was obtained at $0.1\ m$ away from the blades at the entrance of the diffuser for all the studied cases. Table 1 lists the main specifications of the simulated turbine.

Table 1.
General specification of shrouded turbine design.

Rotor diameter for SWT	2.4m
Rotor diameter for BARE	2.4 m
Rotor area	4.524 m^2
Diffuser length	0.5 m
Outer radius	1.4 m
Rotational speed	20 rad/s
Brim angle	+10
Wind speed	4 m/s
Density	1.225 kg/m^3

2.4. Geometry Modelling and Mesh Computational Domain

In this section, as there are five models have to be tested and simulated, hence five automatic meshes based on the interior nodes and elements automatically were created, to increase the accuracy as well as enhances the speed of simulation. Figure 5 presents the mesh computational domain of the studied designs. It is important to make sure that well-designed mesh could provide accurate and efficient numerical solutions, while a poorly designed mesh could lead to inaccurate or unstable results.

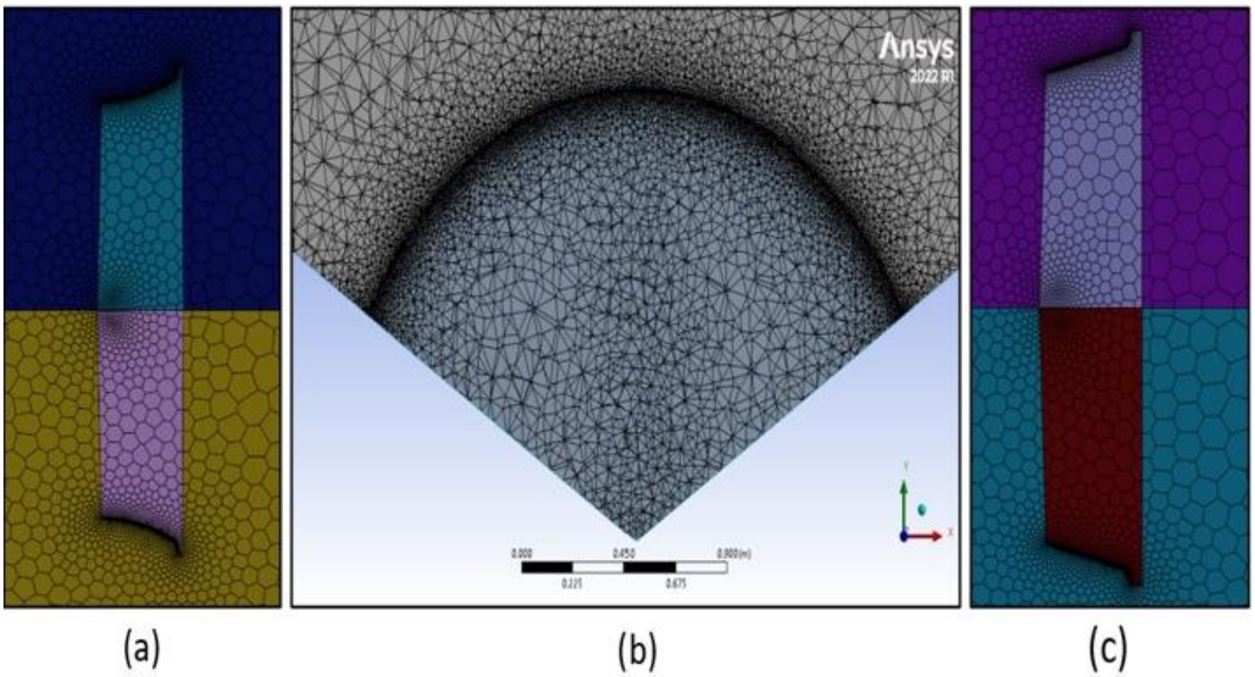

Figure 5.
Mesh distribution of shrouded wind turbine.
Note: (a) Curved diffuser with brim.
(b) Straight diffuser without brim.
(c) Straight diffuser with brim.

3. Simulation

The simulation process was conducted to study the changes on the wind speeds, air pressure, as well as the behavior of the wind currents which passes through the turbine for four different cases.

From Figure 6, it was observed that the speed experienced a 15.751% increase in the instance of a straight diffuser without a brim. However, this percentage rose to 21.98% upon the addition of a brim. It's clear that, the addition of a diffuser will reduce the velocity behind the turbine, as depicted in figure 8. This caused the formation of a low-pressure area as shown in Figure 9, leading to an increase the pressure difference between the inlet and the outlet. Consequently, the mass flow rate will be increased resulting in a higher output power.

Similarly, in the case of a curved diffuser without a brim, there was a significant increase in the wind speed which reaches up to 16.659%. Subsequently, the inclusion of a brim resulted in a further boost, reaching 23.695%.

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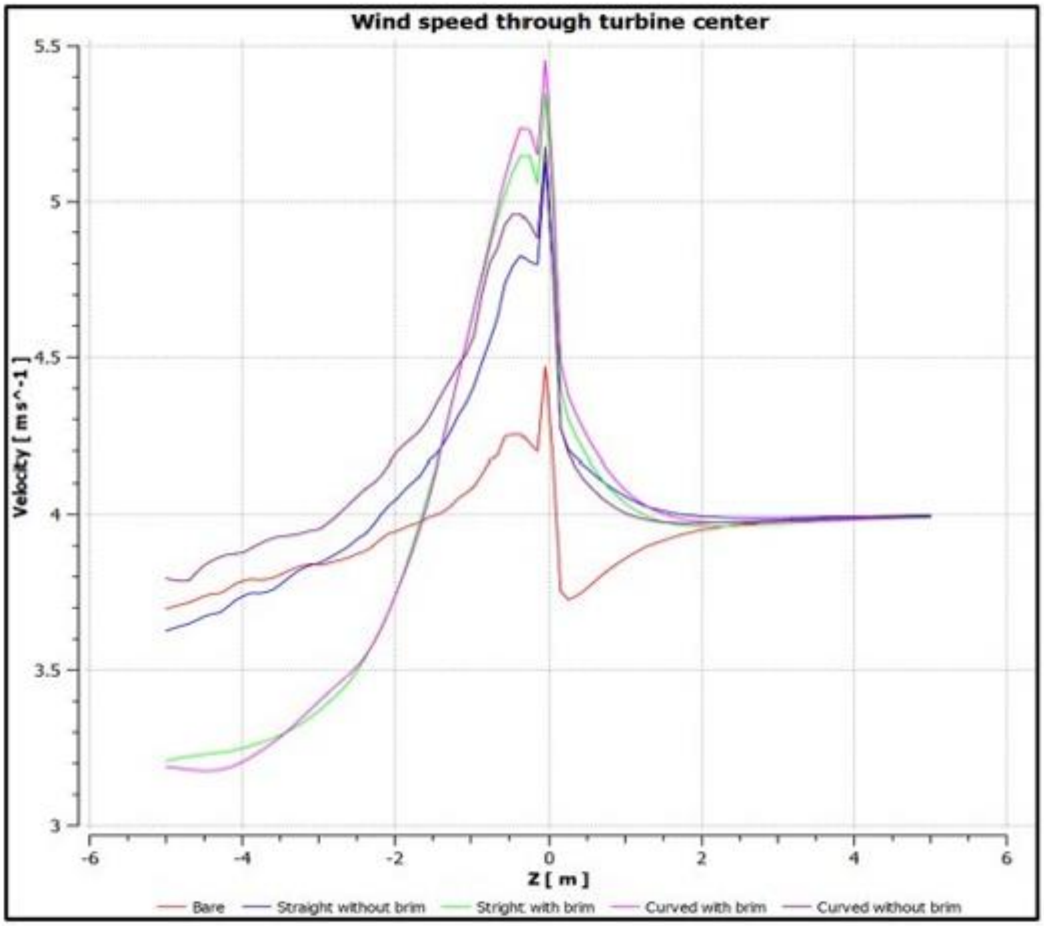

Figure 6.
The wind speed variation through shrouded turbine.

It's clear that as mentioned previously the thermal images in figure 7 and figure 8 depict the pressure levels and the extent of pressure variation between different designs. In the case of the straight diffuser without a brim, the pressure decreased from $-2.4\,Pa$ in case of bare turbine to $-6.1\,Pa$, whereas with the addition of a brim, the decrease in pressure was $-6.2\,Pa$. As for the curved diffuser, the pressure decrease was $-7.5\,Pa$ without a brim, and it further reduced to $-7.75\,Pa$ with the inclusion of a brim. Thus, the bending of the diffuser body reduced the pressure behind the turbine. Also, the brim successfully accomplished the intended task of creating vortices, resulting in the formation of a low-pressure area.

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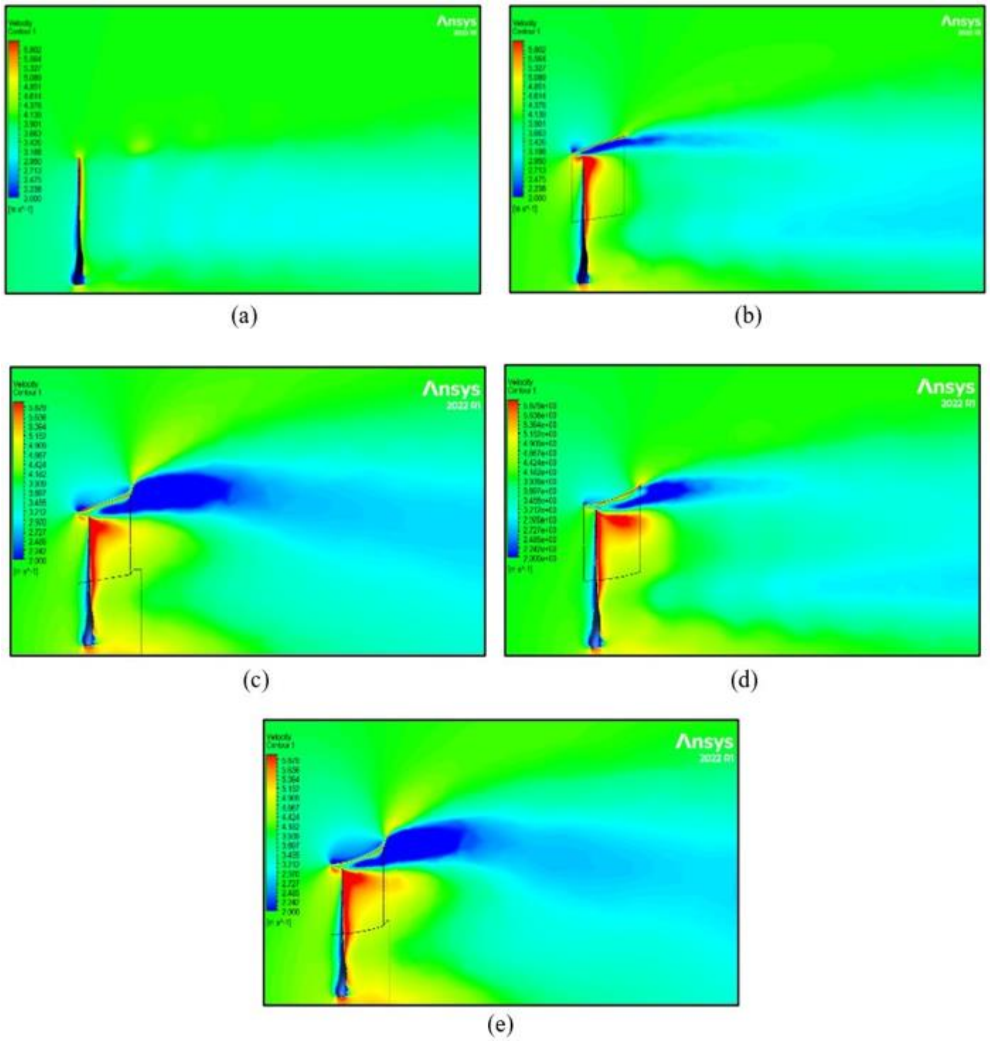

Figure 7.
Wind speed contours across the shrouded turbine.

Note: (a) Conventional rotor.
(b) Straight diffuser without a brim.
(c) Straight diffuser with a brim.
(d) Curved diffuser without a brim.
(e) Curved diffuser with a brim.

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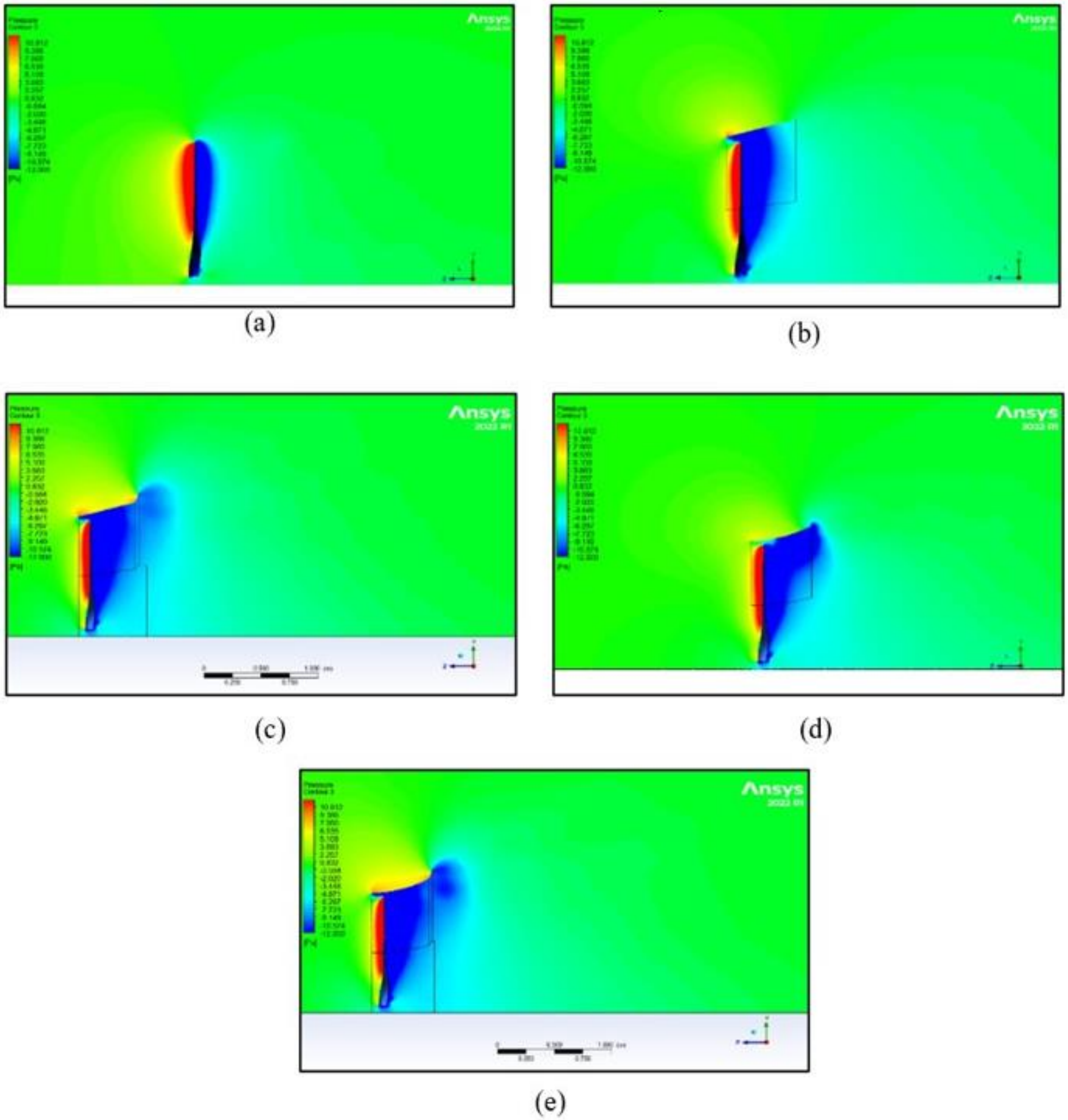

Figure 8.
Pressure contours across the shrouded turbine.
Note: (a) Conventional roto.
(b) Straight diffuser without a brim.
(c) Straight diffuser with a brim.
(d) Curved diffuser without a brim.
(e) Curved diffuser with a brim.

To figure out the differences between the four designs in terms of the pressure distribution near the center of the rotor, figure 9 shows the pressure distribution through the turbine for the studied cases

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which indicates the results obtained previously where the curved diffuser with a brim design has a significant decrease in the pressure then higher wind speeds.

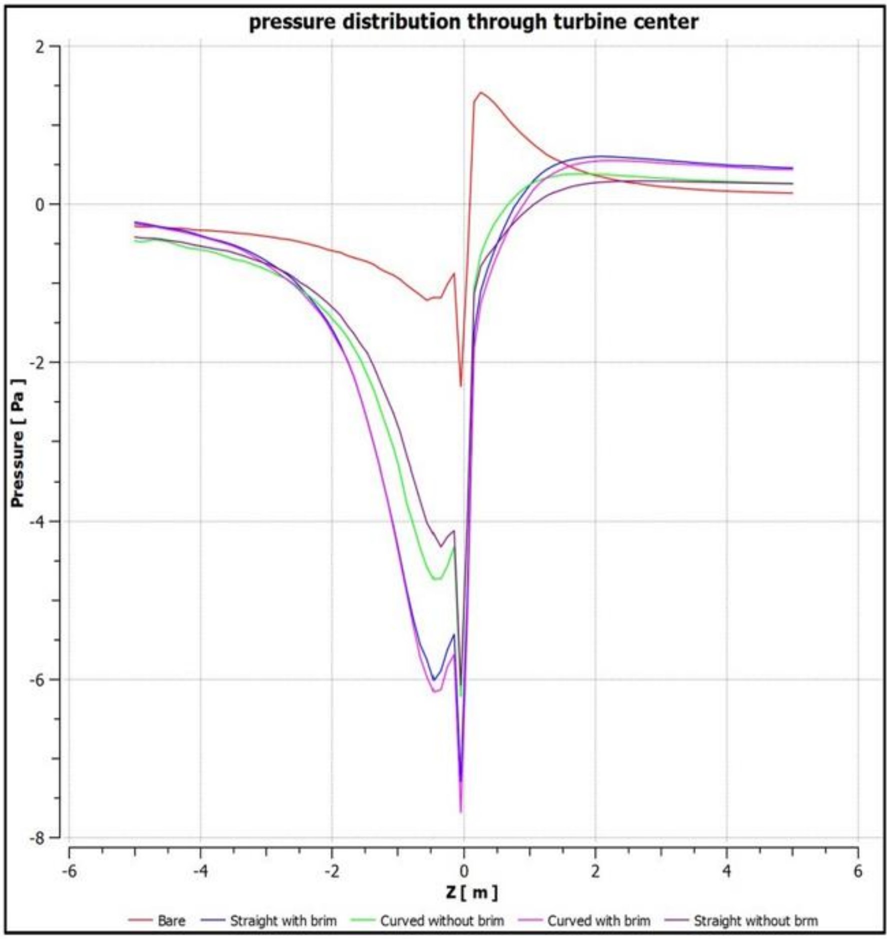

Figure 9.
Pressure distribution through shrouded turbine.

The decrease in velocity behind the turbine is due to the formation of an air vortex behind it which explains the low- pressure area which formed as shown in figure 10. The brim will act as an obstacle in front of the wind, so when the wind collided with the brim a formulation of vortex behind it will be produced as shown in figure 10c and figure 10e.

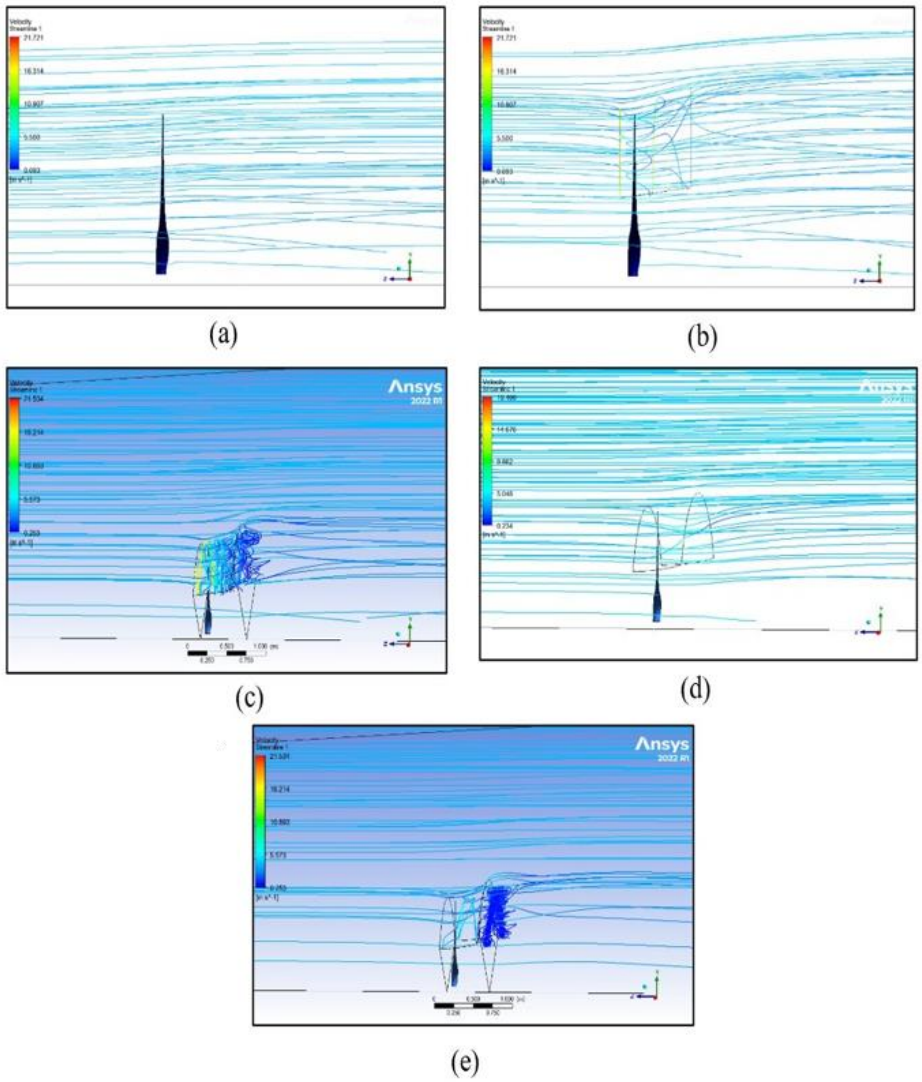

Figure 10.
The streamlines across shrouded turbine.
Note: (a) Conventional rotor.
(b) Straight diffuser without a brim.
(c) Straight diffuser with a brim.
(d) Curved diffuser without a brim.
(e) Curved diffuser with a brim.

4. Results

This section discussed the results obtained from ANSYS simulations, which revealed changes in wind speed, pressure, and flow pattern for each of the studied cases. It is clear that the diffuser design with brim has the highest angular velocity compared to the other designs. Furthermore, adding the brim has a significant increase on the power coefficient which reaches up to 85%. While observing the results, it was clear that the speed experienced a 15.751% increase in the instance of a straight diffuser without a brim. However, this percentage increased up to 21.98% upon the addition of a brim. Similarly, in the case of a curved diffuser without a brim, there was a significant increase reaches

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16.659% in wind speed. Subsequently, the inclusion of a brim resulted in a further boost, reaching 23.695%. In the case of the straight diffuser without a brim, the pressure decreased by 165.217%, whereas with the addition of a brim, the decrease amounted to 169.565%. However, for the curved diffuser, the pressure decreases by 219.565% without a brim, and a further reduction obtained by 236.957% in the case of adding a brim. The variation of the wind speeds and the pressure levels across the studied cases will directly affects the output generated power. Specifically, the output power of $84.916\ W$ for the straight diffuser without a brim, and increased up to $134.946\ W$ while adding the brim. In addition, in the case of the curved diffuser without a brim, a $100.756\ W$ output power could be obtained, while with the inclusion of a brim, it reaches up to $147.357\ W$.

Figure 11 illustrates the impact of increasing tip speed ratio on Cp for the studied cases. It is observed that increasing TSR initially leads to an increase in the power coefficient, surpassing 83% in the case of the curved diffuser with a brim of $8\ rad/s$ TSR. However, beyond this point, the Cp starts to decline for all cases, except for the curved diffuser without a brim and the straight diffuser without a brim. For the remaining three cases, the decline in Cp occurs when the TSR exceeds $7\ rad/s$ for the curved diffuser without a brim and the straight diffuser without a brim, and $5\ rad/s$ for the bare turbine. This decrease can be attributed to several reasons, with the primary factor being the increase in drag force due to the enlarged area created by the addition of the diffuser. The increased TSR also causes flow separation along the blade surface, which reduces the lifting force. It is important to note that these specific variations depend on the turbine's design so it may vary accordingly.

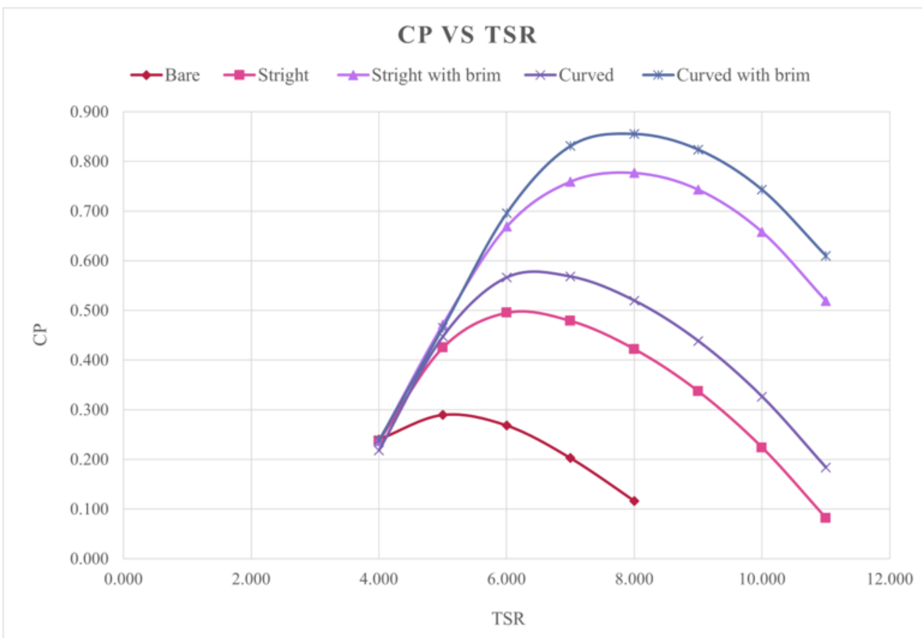

Figure 11.
Relation between Cp and TSR of shrouded turbine.

As a results of the simulations and the mathematical analysis of the studied designs it is clear that a good correlation has been achieved in terms of the power coefficient and the output generated power of the curved diffuser with a brim shrouded wind turbine as shown in figure 12.

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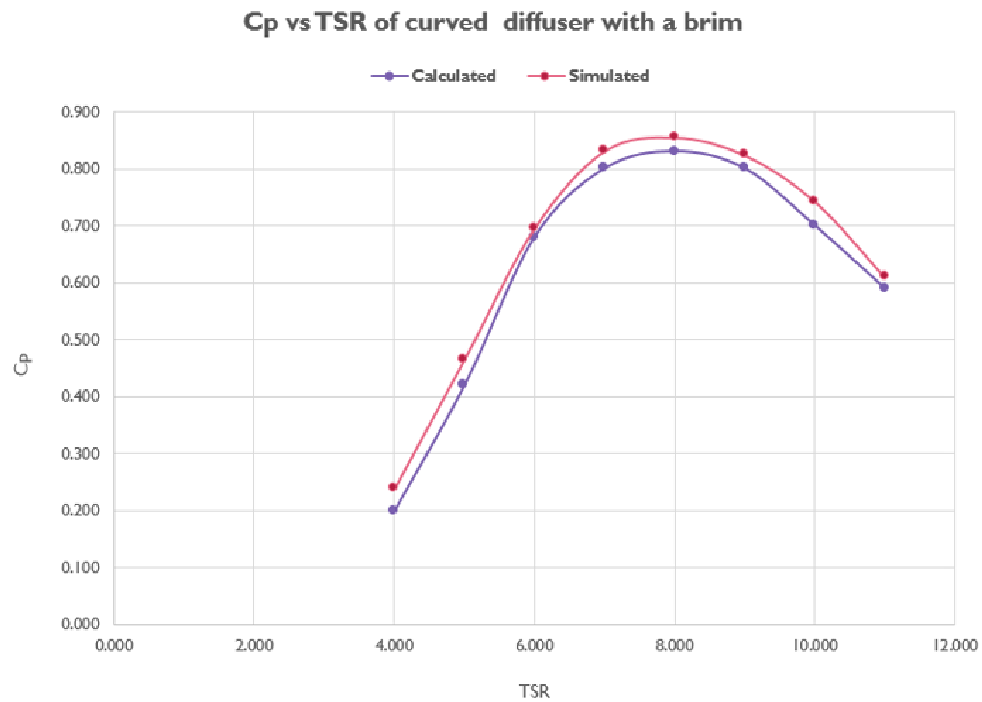

Figure 12.
The correlation between the calculated and simulated Cp of the curved diffuser with a brim shrouded turbine.

5. Conclusion

The development of shrouded wind turbines is an important step towards making wind energy more accessible and viable in areas with low wind speeds. This study has shown that adding a diffuser and a brim to wind turbines can significantly improve their performance and increase power output. The brim acts as an obstacle, accelerating the airflow through the turbine, which enhances efficiency. The design with a curved diffuser and brim has achieved the highest wind speed compared to the other designs. There is an increase in wind speeds compared to the conventional horizontal wind turbine by 23.69%, thus, the output power will increase by 310.12%. As a result, the power coefficient of the curved diffuser with a brim reaches 83.1% whereas, the conventional turbine design achieved 20%. These findings highlight the importance of the wind turbine's design improvements to enhance the performance and efficiency of wind turbines.

Many different adaptations, tests, and experiments have been left for the future, as more studies could be conducted to enhance the shrouded wind turbine performance by focusing more on the diffuser length, brim angle and brim length, which may have increase the efficiency of the designed turbine. In addition, the manufacturing materials of designing the diffusers may solve the problem of prohibitive cost. On the other side it is important to test the performance of shrouded turbine which installed in a different wind speed regimes. These turbines have the potential to revolutionize the way that the electricity has been generated, providing a clean and sustainable source of power for generations to come.

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