A CFD Study of a Flanged Shrouded Wind Turbine: Effects of Various Flange Surface Types on Output Power

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There is a global trend to optimize energy harvesting from all energy resources including renewable energy. In this study, the focus is on improving the surface of flanges in flanged shrouded wind turbines to obtain more efficient systems. A CFD approach is utilized for this purpose. All models are identical in the entrance diameter, exit diameter, length of the diffuser, and the height of the flange, but each model is of a different flange surface type. Different surfaces are studied, including a simple surface and some furrowed surfaces. The validation reports that there is a strong correlation between the present study's outcomes and that of previously experimental results. The results show that the models with furrowed surface flange type lead to an increase in the wind velocity when approaching the wind turbine blades. This leads to about 5-7\% more output power. Also, the results indicate that the maximum velocity occurs at about 5cm after the shroud entrance. Consequently, it is suggested that the wind turbine should be installed at that location inside the shroud, to obtain the optimum energy harvest.

Keywords: wind energy, shrouded wind turbine, flanged shroud, furrowed surface flange.

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1. Introduction

Combustion of fossil fuels to support energy, results in several environmental problems, such as climate change, smog, and acid rain. Recently, worldwide efforts have been made to reduce global reliance on fossil fuels. Hence, this concern drew attentions toward renewable energy resources.

Wind energy is a potential source of renewable energy. Nowadays, wind generator turbines possessing various sizes are increasingly manufactured. A difference between small and large scale wind turbines is that the small scale wind turbines are usually used for supplying the required power, often within a pre-determined setting and not where the wind is most satisfactory. The turbines should enhance their energy capture to obtain rational power outputs from small scales, mainly at low wind speed. They should also be reactive to the alterations in the wind direction.

2. Literature review

The power generated by a wind turbine is proportionate to the cubic power of the wind speed. Hence, the energy output is greatly increased by a small increase in wind speed. Thus, researchers attempt to increase the speed of wind in the vicinity of wind turbine blades via various methods. The ducted or shrouded wind turbine is a common technique to improve the captured power.

Many research have been done in this area but still there are notable aspects of view that could be considered experimentally and numerically [1-5]. A theoretical work was performed by Railbird and Lilley to obtain power outputs from a completely ducted land type wind turbine (sixty-five percent of the highest power outputs of the ideal bare wind turbine) [6]. Using a blowing at the intake of the shroud and an airfoil formed ring-flap at the diffuser outlet, flow separation was prevented and the power production was increased in the study by Igra [7]. 20% increase of power output was obtained when a blowing was used at the intake and a 65% increase in power was obtained when an airfoil-shaped ring-flap was used. Igra also experimentally studied a shrouded aero generator in a wind tunnel [8]. The model generated power about 100% more than that of produced by a perfect wind turbine in the same situations. An economic and technical work was performed by Foreman et al. on the diffuser increased wind turbine (DAWT) [9]. They attained a considerable power increase from DAWT, two
times greater than the power generated by the bare wind turbine. The increased power was created as a result of the low pressure at the exit of the diffuser pumping a great deal of air via the DAWT as compared to a usual wind turbine.

The parameters affecting the performance of the diffuser system within the wind tunnel were assessed in the study of Gilbert et al. [10]. The first DAWT generation in their work produced power that doubles the usual WECS (wind energy conversion system) when subjected to operating conditions similar to those presented by Igra [8]. The performance and design of an axial flow turbine were calculated by Igra and was found to be appropriate for the suggested shrouds [11]. The power generation augmentation factor was within the range of 2-4. Theoretical, experimental, and numerical examinations were performed by Phillips et al. on a Vortec 7 wind turbine, and a comparison was made between former and the experimental works [12]. It was found that there was an agreement between field measurements and CFD. Numerous field outcomes were also consistent with the former investigation results. A comparison was made by Hansen et al. between the CFD calculations of a bare turbine and the theoretical equation expressing the power coefficient as a function of the thrust coefficient [13]. It was observed that the Betz limit can be surpassed with a ratio relative to the increase in mass flow rate when implementing duct. Ohya and Abe studied the flow fields around a flanged diffuser by utilizing CFD for developing small-type 1.5-kilowatt wind turbines [14]. Comparing the findings with the equivalent existing statistics indicated that the design of Ohya and Abe was capable of offering rational predictions for the complex turbulent flow. Hence, it can be shown that the performance of a flanged diffuser intensely relies on the loading coefficients and the opening angles. In the research by Ohya et al., it was found that the hollow-structure diffusers act as the shroud-type wind turbines to collect and accelerate the wind [15]. Moreover, they indicated that utilizing a flange with an appropriate height linked to the outer boundary of the diffuser exit attained a significant increase in wind speeds. The reason for this increase in speed can be attributed to the low-pressure region created within the exit area of the diffuser due to the vortex creation drawing the wind toward the diffusers [15]. Numerical and experimental assessments were performed by Abe et al. for the flow field of small wind turbines possessing flanged diffusers [16]. They showed that the wind turbine with a shrouded diffuser had a power coefficient almost four times greater than the bare wind turbine. Moreover, this wind turbine had an increased power output mostly due to the acceleration of the pending wind via a flanged diffuser. In the study of Matsushima et al., the impacts of a frustum-formed diffuser on the output power of small wind turbines were investigated numerically and experimentally [17].
They indicated that the considered diffuser parameters could increase the highest wind speeds at the entrance of the diffuser by about 1.7 times. Moreover, the highest energy production ratios of around 2.4 times were acquired by gathering wind energy into the turbine. A scoop was used by Wang et al. for improving the energy capture from a wind turbine with low wind speed. They utilized physical tests performed in a commercial CFD code and boundary layer wind tunnel to obtain an optimum scheme for the scoop. The ultimate scoop design increased the airflow speeds by 1.5 times corresponding to an increase in power outputs of 2.2 times with equivalent swept areas [18]. Nair and Raj developed and analyzed a three-dimensional CFD model for shrouded wind turbines with flanges using GAMBIT within FLUENT commercial software [19]. They demonstrated an acceptable similarity between former experimental works and their numerical investigations. A very compacted and brimmed diffuser was developed by Karasudani and Ohya, which gave an output power two to three times higher than the conventional wind turbines [20]. PIV and numerical simulations were investigated by Kardous et al. to reach a deeper understanding of the effects of the flange heights on the increases in the velocity of wind at the inlet of a flanged diffuser. They found the role of the flange in increasing the wind in the diffuser at the inlet segment [21]. The increase in the rate of the wind velocities by the diffuser with no flanges was around 58%; however, this increase was within the range of 64-81% for the flanged one, and it seemed that the flange height had no considerable impact on increasing wind velocities the ratio of the flange height to the throat diameter equal to 0.1. El-zahabi et al. numerically studied the effects of flange angle on the output power of shrouded wind turbines. They found that an angle of 15 degrees resulted in the best efficiency [22]. In a different research, effects of number and attack angles of blades on rotational speed were experimentally studied in a duct [23]. The results showed that wind velocity increased up to 2.46 times numerically and 2.32 times experimentally in the optimized case. Angle of attack of 75 degrees and 3 blades turbine were resulted in the most efficient case. In another work, a small wind turbine was studied experimentally at low speeds in the range of 2.5-4.5m/s [24]. Different blade numbers were tested including 2, 3 and 4 blades. The results indicated that wind turbine with diffuser and 3 blades shows the best performance. Another idea was investigated comparing a wind turbine with a diffuser, with a wind turbine with a diffuser and an inlet shroud [25]. The outcomes demonstrated that the most increase of power efficiency was achieved in the case of the wind turbine with diffuser and inlet shroud and it was about 41%.
N. K. Siavash et al. proposed a new mathematical model of shrouded wind turbines. They reported that an optimized shrouded wind turbine may experience a power coefficient of 0.93 in the best situation [26]. A comparative study was performed by Maftouni et al. on three different models for a large-scale wind turbine, namely bare, simple shrouded, and flanged wind turbines. Their results indicated that implementing a simple shroud led to a 106% increase in output power, and the use of a flanged shroud led to a 137% increase [27]. Khamlaj et al. performed a numerical optimization of the wind turbine by varying the diffuser curve and the flange height to increase the output power. They used the multi-objective genetic algorithm method for optimization [28]. Lipian et al. designed an innovative wind system including two small rotors inside a shroud [29,30]. The outcomes demonstrated that, while augmenting the wind turbine performance, using shroud increased the load on the rotor. An application of the second rotor was proposed to reduce this shortage. It provided a modest increase in efficiency (about 12% for the bared turbine and 5% for shrouded turbine) but resulted in an evener load distributed on the rotors.

In the current research, a numerical study is performed to illustrate the effects of shrouded flange surface types on the velocity of the wind entering the shroud or approaching the turbine. Different surface types are studied and output power is calculated in each case. Here, the main goal is to find the optimum surface type of the flange for the first time in the literature.

3. Materials and Methods

In the present study, a CFD analysis is performed to find the best surface type for the flanges in shrouded wind turbines. Here, the flow is considered unsteady, incompressible, turbulent, and 2D. A k-ε model is considered to simulate turbulence.

Figure 1 shows the schematic of a flanged shroud. The dimensions of the solution domain, shown in Figure 2, are chosen according to the research by Abe and Ohya [14]. Table 1 presents the dimensions of the shroud. This design is for optimizing the proposed dimensional relations in Ohya et al. [15].

Figure 3 indicates the boundaries of the problem. To apply proper boundary conditions, \( U=U_\infty \) and \( V=0 \) are assumed at the inlet of the domain (boundary 1). At the outlet of the domain (boundary 5), \( \text{flow}_{\text{in}} \) is assumed to be equal to \( \text{flow}_{\text{out}} \) and the flow is considered incompressible. For the top and the bottom of the domain (boundaries 4) and the walls of the
shroud body (boundaries 3), the no-slip boundary condition is applied and velocities are considered to be \( U=0 \) and \( V=0 \). For boundary 2, a symmetric axis condition is assumed.

A triangle mesh type is used to make the computational grid. To have a reliable grid, the mesh-independence study is performed. The maximum air velocity is calculated for five different grids. The results are reported in Figure 4. It is obvious that there is no difference in the results when increasing the total numbers of the mesh elements beyond 19534. Therefore, the fourth grid is selected to optimize the calculation cost while undertaking accurate results.

For the first time, some different flange surface types are modelled, simulated, and analyzed to achieve the optimum case with the highest maximum velocity. Two views of the meshed systems are reported in Figures 5 and 6. The whole system in the case of a simple flange surface is shown in Figure 4. The detailed mesh near the flange surface is obvious in Figure 5 for the circular furrowed type of the surface.

Figure 7 shows the side views of these surfaces. One model is a simple flange and the other is a furrowed flange with circular furrows of 2 mm diameter.

4. Validation

The base model is validated with the experimental results published by Ohya et al. [10]. The experiment was performed in a subsonic open wind tunnel. The wind tunnel was 3.6 m wide, 2 m high, and 15 m long, and the maximum wind speed in the tunnel was 30 m/s. An I-type hot wire velocity-meter was used to measure distributions of wind speed. To visualize the flow, the smoke-wire method was used.

Here, the shroud is modelled under the same conditions as the experimental study. Figure 8 compares the velocity ratio between local velocity and free stream velocity, \( U=5 \) m/s along the shroud, in both cases of numerical and experimental studies. The variation in the difference between the two graphs, reported in Figure 8, is from 0.21% to 4.3%. Thus, good agreement is observable between the simulation results of the present work and the experimental results of Ohya et al. [15].

5. Results and Discussion

For the simple surface and the furrowed surface with circular furrows, the velocity contours are presented in Figures 9 and 10, respectively.

It should be mentioned that because of the small size of the shroud in comparison with the solution domain, it is not possible to see the furrows on the flange in these contours.
The graphs of velocity are shown in Figures 11 and 12 for the simple surface and the surface with circular furrows.

It is observable that implementing a furrowed flange surface type results in a velocity increase in the shroud inlet region. This surface type produces a larger wake and, consequently, a stronger negative-pressure region. Hence, the wind velocity increases more when approaching the turbine.

The velocity graphs also indicate that the maximum wind velocity occurs at about 5cm after the entrance of the shroud. Thus, it is recommended to install the wind turbine at that location.

It should be mentioned that we have also tried some other geometries for the furrow shape, including square and wedge shapes, and found the results to be very similar.

Figures 13 and 14 show the pressure contours of the system for the simple surface and the surface with circular furrows, respectively.

It is observable that the low-pressure region is stronger near the shroud end in the case of the flange surface with circular furrows. Also, the pressure graphs are shown in Figures 15 and 16 for both cases.

The pressure graph for the simple flange surface type shows a pressure about -11Pa at the outlet of the shroud, while this is about -13Pa for the flange surface with circular furrows. As it was mentioned before, some other furrow types have been simulated and tested and similar results were obtained. It is observable that making furrows in any shape leads to the presence of more vortexes and consequently a larger pressure drop. So the velocity will be increased to compensate for the pressure drop by sucking more mass of air through the shroud. The power harvested by a horizontal wind turbine is proportional to the cube of the wind velocity. Thus, the generated power in each case can be calculated based on this. The results are very similar, and in all cases, an increase of about 5-7% is observed in the harvested power for all of the furrowed surface types in comparison with the simple-surface flange.

6. Conclusion

The flow characteristics in the shroud of a wind turbine and around it for various flange surface types was studied numerically. Results indicate that there is a pressure drop in all cases, representing a region with negative pressure. This negative pressure is more sensible in the case of the furrowed flange surfaces. Hence, the air velocity increases more when entering the
shroud in these cases. The expected power increase for the furrowed flange surface types is about 5-7% when compared with the shroud with a simple-surface flange. The results also indicate that no significant difference in power increase is observed due to various shapes of the furrows including circular, square, and wedge types. In all of the cases, the maximum wind velocity occurs at about 5cm from the shroud entrance. A strong correlation was observed when the simulated results were compared with the experimental results obtained from the literature. For that reason, it is proposed that the wind turbine is placed at that location. Regarding simple geometrical modifications required to achieve the furrowed surface type of flanges, both for new shrouded wind turbines and old ones, the results of this study can be used in industrial applications.

7. Nomenclature

\[ U \]: Horizontal velocity \[ m/s \]
\[ V \]: Vertical velocity \[ m/s \]
\[ U_\infty \]: Infinity Velocity \[ m/s \]

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BIOGRAPHIES

FIGURE CAPTIONS

Figure 1. Schematic of a flanged shroud.
Figure 2. The solution domain and schematic of the problem.
Figure 3. Schematic diagram of the boundaries in the system.
Figure 4. Mesh independency study results.
Figure 5. A view of the meshed system (flange with the simple surface).
Figure 6. A view of the meshed flange surface with circular furrows.
Figure 7. Different flange surface types: a) simple flange surface, b) furrowed flange surface.

Figure 8. Comparison of CFD results and experimental data of Ohya [15].

Figure 9. The velocity contour for the case involving a flange with a simple surface.

Figure 10. The velocity contour for the case involving a flange with a furrowed surface with circular furrows.

Figure 11. The graph of velocity for the simple flange surface.

Figure 12. The line graph of velocity for the flange surface with circular furrows.

Figure 13. The pressure contours of the system for the simple flange surface.

Figure 14. The pressure contours of the system for the flange surface with circular furrows.

Figure 15. The graph of pressure for the simple flange surface.

Figure 16. The graph of pressure for the flange surface with circular furrows.

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Table 1. Dimensions of the simulated shroud.

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TABLES

Table 1. Dimensions of the simulated shroud.

| Dimension            | Value   |
|----------------------|---------|
| Inlet diameter, $D_1$| 20 cm   |
| Outlet diameter, $D_2$| 24 cm   |
| Length of shroud, $L$| 30 cm   |
### Thickness Table

| Description          | Value |
|----------------------|-------|
| Thickness of shroud  | 2mm   |
| Thickness of flange  | 4mm   |
| Height of flange, h  | 5cm   |

**BIOGRAPHIES**

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